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COMPARISON OF MEASURED AND MODELLED RADIANCES OVER STRATOCUMULUS CLOUDS

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1. INTRODUCTION

The evaluation of effects of cloud inhomogeneities on their radiative properties is of substantial importance for a better understanding of clouds' critical contribution to the Earth's radiation budget. The solar radiative transfer in warm clouds is a complex function of the distribution of cloud liquid water and of the drop size. Even in stratiform clouds, cloud structure is typically remarkably inhomogeneous, and recent studies have shown that these inhomogeneities can significantly affect the bulk radiative properties of the clouds.

The idea of this study is to measure short-wave radiances above stratocumulus cloud fields together with detailed cloud microphysical observations, and subsequently to compare the measured radiances to radiances modelled by using the measured microphysical and cloud structure information as input to sophisticated three-dimensional radiative transfer calculations. Questions addressed are: Can 3D radiative transfer modelling reproduce the radiance variability measured above a stratocumulus cloud sheet? What should the input cloud to these calculations merely account for (2D structure, 3D structure, or cloud top structure)?

2. AIRBORNE MEASUREMENTS

The measurements were carried out onboard the Met Office C-130 Hercules aircraft over sea areas near the British Isles on 22 February 2001. On that day extended stratocumulus cloud fields were present in altitudes between 500 m and 950 m. No higher clouds were present, which could have influenced the incoming solar radiation.

The clouds' microphysical characteristics (drop size distribution, liquid water content [LWC]) and their structure (variations of LWC, geometrical depth) were observed using a Fast FSSP (Forward Scattering Spectrometer Probe) and a Nevzorov Probe. The horizontal resolution of the measurements was 100 m due to the aircraft ground speed of around 100 m/s and measurement frequencies of 1 Hz. The stratocumulus clouds showed an adiabatic liquid water content (LWC) profile with an average liquid water content of 0.41 g/m^3, a liquid water path of around 180 g/m^2, a medium effective drop radius of 10 μm, and a droplet number concentration of 110/cm^3. In Figure 1a the measured LWC variability is shown for a horizontal flight within the cloud at an altitude of around 700 m (60 km horizontal distance). The average LWC varied by +/-26% standard deviation.

Spectral radiance measurements were done with a nadir looking Short-wave Spectrometer (manufactured by Zeiss/Germany) measuring in two wavelength ranges between 300 and 950 nm (resolution of 3 nm), and 950 and 1700 nm (resolution of 6 nm). The instrument allows a full spectral measurement with frequencies from 1 up to 10 Hz; here 5 Hz measurements were done and averaged over 1 s (gives 100 m horizontal resolution). The flight pattern contained a number of vertical profiles through cloud as well as horizontal flights inside and above cloud level to characterise both the cloud inhomogeneity and the variability of up-welling radiances above cloud.

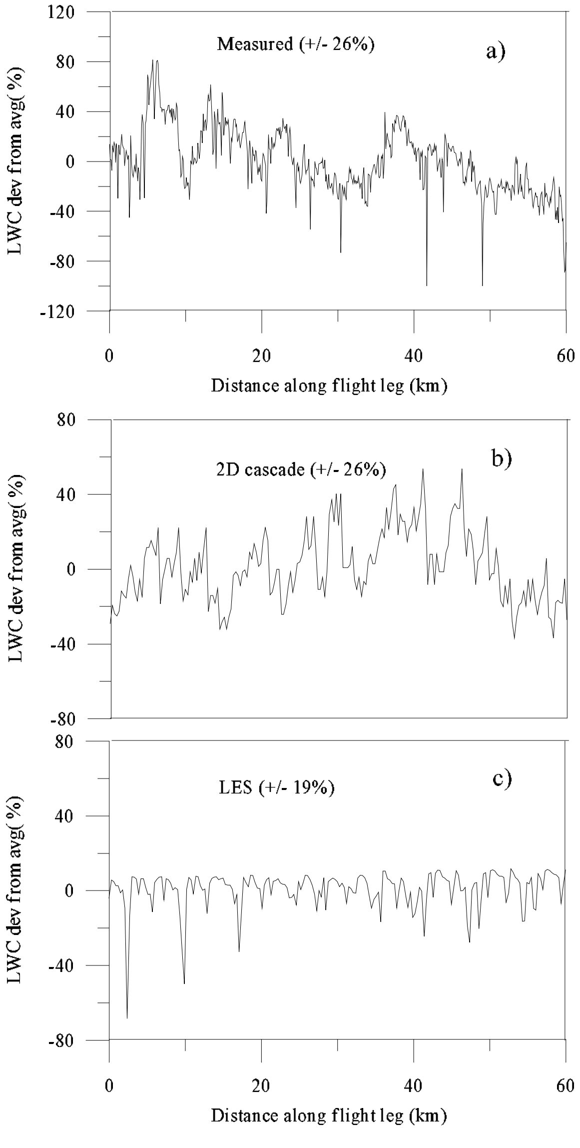

Figure 1. Measured (a) and modelled (b-c) LWC variability in the marine stratocumulus cloud sheet measured on 22/02/01 near Ireland.

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Figure 2a shows the variability of up-welling radiances at 550 nm wavelength, measured for a horizontal flight at 1.2 km altitude (around 250 above cloud). The average radiance of 14.6 W/m^2/sr/μm varied with a standard deviation of +/-22% along a 60-km-long flight leg.

3. 3D RADIATAIVE TRANSFER MODELLING

The SHDOM radiative transport code (*Evans, 1998*) was used to calculate the radiances reflected from the inhomogeneous stratiform clouds.

The clouds, used as input to these calculations, were built up with either a 2D-bounded cascade model (*Cahalan et al., 1994*) based on the measured cloud microphysical statistics or by using cloud fields from Large Eddy Simulations (LES). The following model clouds were used:

- 2D-cascade modelled cloud field (horizontal cloud top),
- 2D-cascade modelled cloud field with superimposed wavy top (an absolute sinus wave with amplitude of 50 m, corresponding to typically measured "ups-and-downs" at cloud top),
- LES modelled cloud, and a
- LES-hybrid = LES modelled cloud with superimposed, more wavy cloud top taken from *Moeng et al. (1996)*.

All model clouds, used as input to the radiative transfer code, were strained to have the main characteristics/average values identical to the measured cloud sheet, e.g. vertical extension, an adiabatic liquid water content profile, average LWC and droplet number concentration.

Radiative transfer calculation were done at different wavelength (550 nm, 890 nm, 1600 nm); here we focus on the modelling at 550 nm. The horizontal domain used was between 3.6 km x 3.6 km and 6.4 km x 6.4 km, and periodic boundaries were used. Additionally, a sea surface albedo of 4% was used (Lambertian reflection) and the solar zenith angle was set to 61 degrees in agreement with the average value during the radiance measurements above cloud.

4. RESULTS

2D-cascade modelling is capable to realistically describe the horizontal LWC variability in cloud. Figure 1b shows the LWC variability for an imaginary flight through the 2D-cascade modelled input cloud field (zigzag flight with overall length of 60 km) at the same height at which a horizontal measurement flight (Fig. 1a) was performed. Like the measurements, the modelling shows a LWC variability of +/-26%. Despite this, as shown in Figure 2b, the radiance variability above cloud is too low compared to the measurements (4% vs. 22%).

Using LES simulated cloud fields as input to the radiative transfer calculations allows to include more vertical cloud structure as well as more cloud top structure. Three-hour LES calculations were done (from 10:00-13:00 local time on 22/02/01) to build up the LES cloud field, thereby including airborne-measured meteorological information, e.g. temperature and pressure profiles, cloud base and top heights, wind components, and cloud top inversion strength. Figure 1c shows an imaginary

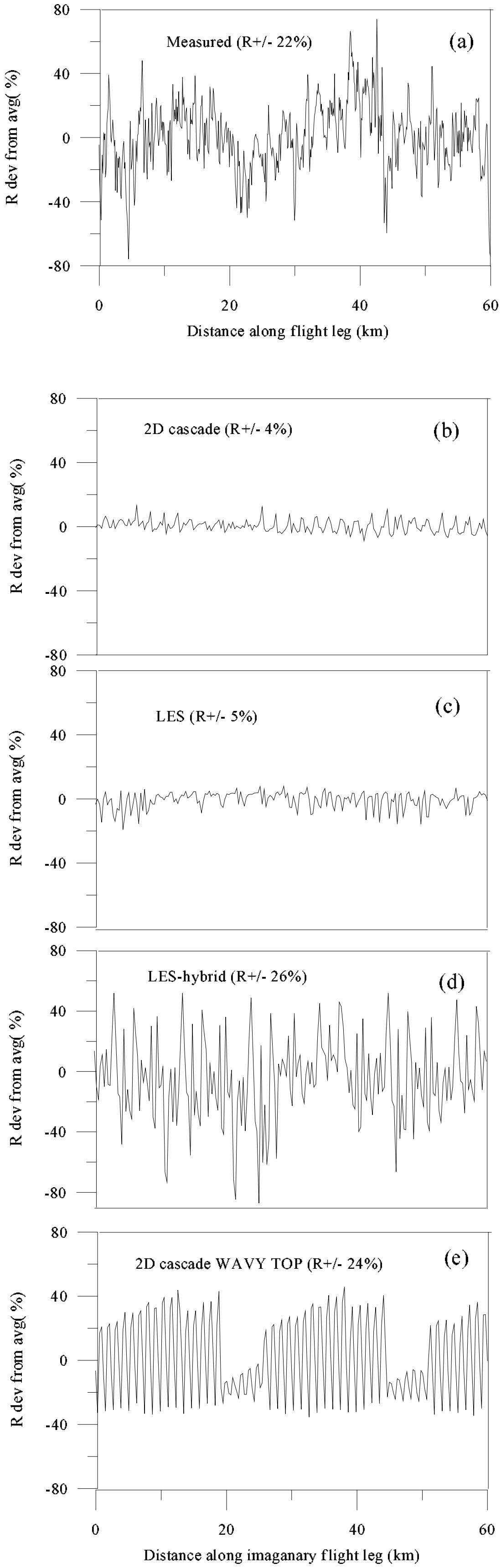

Figure 2. Measured (a) and modelled (b-e) radiance variability over the marine stratocumulus cloud sheet measured on 22/02/01 near Ireland.

horizontal flight through the LES cloud. The LWC variability is somewhat lower than measured. The cloud top is still rather flat, but of course rougher that the flat 2D cascade modelled cloud top. Figure 2c shows the radiance variability above the LES modelled cloud. With 5% standard deviation, the radiances vary still much less than the measurements indicate. Trying to use an LES modelled cloud with a resolution much higher than the measurements as input (20m x 20 m horizontally) only slightly increases the modelled radiance variability above cloud to 7%.

The main reason for the radiance variability being too low is identified as to be the under-representation of actual cloud top structure ("wavy cloud top") by both the 2D-cascade modelling (flat cloud top) and the LES modelling (nearly flat cloud top). This can be seen in Figure 2d were a more realistic cloud top is superimposed on the LES cloud (LES-hybrid cloud), showing a radiance variability which agrees well with the measured one (26% vs. 22%). This finding is supported by the radiance variability computed when imposing a wavy cloud top on the 2D cascade modelled cloud (Figure 2e). Here the radiance variability is 24% and therefore at the same magnitude as found in the measurements.

The comparison of radiance variability over cloud at different wavelengths gave only quantitatively slightly changed results.

Additionally, we investigated the potential effects of aircraft attitude changes onto the radiance measurements (spectrometer points in different directions due to aircraft movements during a horizontal flight above cloud). Modelling the reflected radiances for a combination of aircraft roll and pitch angle of 5 degrees, which is an appropriate maximum value during the flights made, and different aircraft headings, revealed changes of radiance variability being negligible compared to cloud top structure effects (<2% standard deviation change).

Comparisons of 3D radiative transfer with measurements have rarely been done in previous studies. Two theoretical papers anticipated shadowing and side illumination "radiative roughening" effects (*Zuidema and Evans, 1998*; *Varnai, 2000*). According to these papers, the importance of cloud top topography that was found in our study is a result of the sun angle, being low enough to impose those effects. Our investigation gives measurement-based support to the results of these theoretical assessments.

5. SUMMARY AND OUTLOOK

This study uses aircraft-based measurements of cloud and radiation parameters together with sophisticated 3D radiative transfer modelling. We focus on the comparison of measured and modelled radiance variability over stratocumulus cloud.

The study suggests that accounting for horizontal (2D) cloud inhomogeneity in the input is insufficient to reproduce the measured radiance variability above cloud. The computed radiance variability is much lower than the measured one. Including LES modelled clouds (more vertical and cloud top structure, but still without realistic 'wavy' cloud top) gives slightly improve results, but still a much lower variability than measured. Only assuming a cloud top with realistic structure, i.e. a rough, wavy cloud top, allows a good agreement between measured and modelled radiances. The cloud top structure dependence of radiance variability above cloud, found in this study, is in line with findings in recent theoretical papers.

In future, along with the total variance, we are going to include a scale analysis (power spectra) of the observed and modelled data. Furthermore, from autumn 2002 on, the new Met Office aircraft will be flying, enabling us to measure further cases of inhomogeneous clouds and surrounding radiance fields. [Currently, the former C-130 Hercules Aircraft used by the Met Office is getting substituted by a new BAE-146 Research Aircraft.] Then, in addition to radiance measurements, spectral flux measurements of up- and downwelling radiation will be possible. Eventually, the measurements and modelling around well-described inhomogeneous cloud fields can provide a tool to check radiative transfer parameterisations.

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