14. MIXED-LAYER PROFILING WITH LIDAR AND MODELING OF THE AEROSOL VERTICAL STRUCTURE.

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Introduction

Remote sensing with lidar (light detection and ranging, the optical analogue of radar) is a useful tool to measure dynamic variations in the atmospheric boundary layer. Depending on the lidar design various parameters can be determined by remote sensing. Among these are basic quantities such as backscatter and extinction coefficients, but also the concentrations of water vapour and other gaseous species can be measured as well as wind speed and wind direction.

During the HEXMAX experiment a completely automatic computer-controlled lidar system was applied to monitor the mixed-layer, i.e. the rise and the fall of the mixed-layer height, the occurrence of layers and the variations in the backscatter coefficients caused by aerosol density variations. This was achieved by measurements of backscatter profiles to a maximum height of 1 km on a continuous basis, with a frequency of 10 profiles/hour. The system was calibrated to measure absolute values for the backscatter and extinction coefficients.

For safety, the measurements were stopped when the platform was serviced by helicopters or ships and when the BMO aircraft measured nearby. No data are available for the period from October 26 till November 5 (noon) due to malfunctioning of the laser which was replaced.

The statistical analysis of previous measurements has shown that the backscatter coefficients are correlated with aerosol properties. This is confirmed by the good agreement between lidar profiles measured in the North Atlantic and profiles calculated with a vertical aerosol model [De Leeuw, 1988a]. The model is based on a mixed-layer model by Fairall et al. [1982]. It was extended to include the effects of humidity both on the particle fall velocities and on the particle size distribution.

Mixed-layer studies during HEXMAX.

An example of the results is presented in Figure 1, for the period from October 15 till October 21. The Figures are B/W photos of a colour display. Backscatter profiles were written as vertical lines modulated with colour corresponding with the value of the backscatter coefficient. The backscatter is scaled from 0.001 to 1 /km (logarithmically) and is indicated in the colour bar on the left. This scale was chosen to provide best visual contrast for the range of backscatter coefficients measured during the experiment. In this B/W presentation the correlation with the original backscatter scale is not obvious, but nevertheless the features are well reproduced. The altitude is proportional to the length of the lines and runs from 0 to 1000 m (vertical axis). Successively recorded backscatter profiles were written sequentially, thus providing

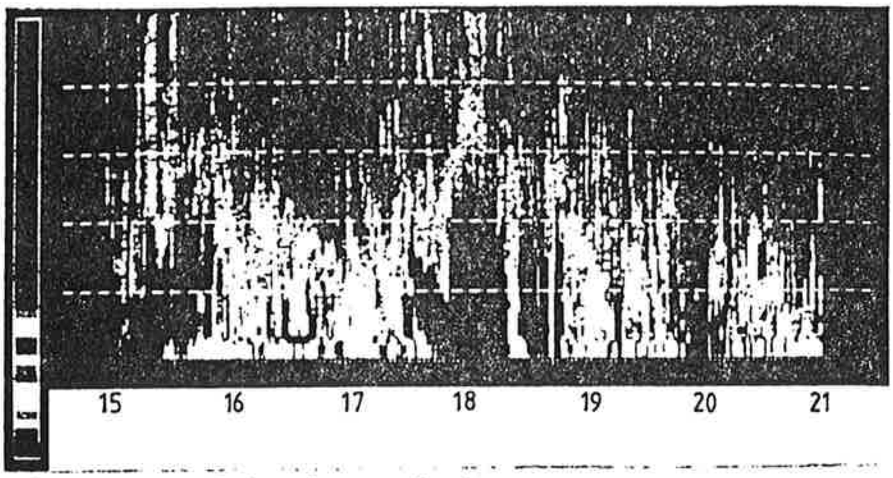

Figure 1. Survey of density variations in the mixed-layer, as deduced from backscatter profiles measured with a 1.06 μm lidar system. The data cover the period form October 15 till October 21. Horizontal axis tics indicate hours, days are separated by vertical lines. The altitude varies along the vertical axis from 0 to 1000 m. The backscatter profiles are written as vertical lines, modulated with colour corresponding with the value of the backscatter coefficient. The correspondence is indicated in the colour bar on the left and varies on a logarithmical scale from 0.001 to 1 /km.

a time scale. The horizontal axis is divided into equal time intervals. Short axis tics indicate the hours, days are separated by vertical lines.

Aerosol density variations are clearly observed, high concentrations appear as dark areas indicating enhanced backscatter coefficients. At the start of the data presentation, in the morning of October 15, the backscatter was relatively high and the mixed-layer height decreased. Around noon a front passed and the wind turned from SW to N. As seen from Figure 1, the layer at the surface was lifted as a whole. The backscatter coefficients first decreased at ground level and later also higher up. The backscatter became very low during a short period, probably because of the advection of unpolluted polar air. This should be confirmed by air mass trajectory analyses. The profiles indicate a sharply confined mixed-layer that is gradually coming down from about 500-600 m in the afternoon of October 16, to about 300 m in the afternoon of the next day.

The reverse was observed in the night from 17 to 18 October, when a layer came down and reached the ground in the early morning. The high backscatter values on October 18 are due to the advection of polluted air from the Dutch industrial areas, as deduced from the wind direction that gradually changed from East to South. When the wind turned further West the backscatter decreased again.

High backscatter values in the storm of October 20 are due to the very high concentrations of sea-salt aerosols. A strong mode was observed in the particle size distributions at exceptional high sizes of 75-100 μm [De Leeuw [1988b]. After the storm the backscatter decreased gradually and the atmosphere became very bright on October 22 (not shown). The NW wind probably brought clear polar air masses and the backscatter became close to the detection limit.

Comparison of a vertical structure marine aerosol model with experimental lidar profiles.

A vertical structure marine aerosol model has been presented in De Leeuw [1988a]. It is based on the balance expression by Fairall et al. Effects of relative humidity on both the particle size distributions and the fall velocities were taken into account.

The model was evaluated by comparison with lidar profiles measured during our 1983 experiments in the North Atlantic. An example is presented in Figure 2. The calculated profile gives the variation of the number of 2 μm particles with respect to the surface concentration. The calculated and the measured profiles are in good agreement. The analysis of 285 profiles shows that the trends are correctly predicted for 65% of the cases. The agreement was less good in 10% of the cases, while the model failed in 25%.

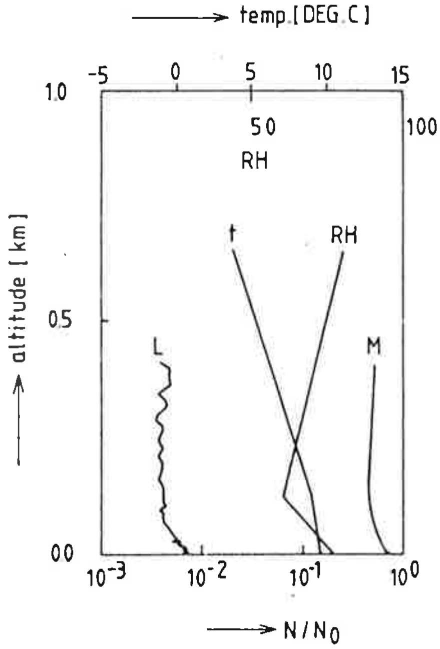

Figure 2.
Comparison of the calculated vertical variation of the concentration of particles of 2 μm in diameter (M) with a 1.06 μm backscatter profile measured with lidar (L). Radiosonde soundings of relative humidity and temperature are plotted as well.
Windspeed u = 9.5 m/s, RH = 76 %, L = -217 m.

Comparison of the model with measured surface layer profiles of particle size distributions.

In the vertical structure marine aerosol model a surface flux relationship has been used that has not been verified thus far, because experimental data on particle profiles in the surface layer were not available [Wu, 1979; Fairall et al., 1983]. In Figure 3 a comparison is made between calculated profiles and data from our 1983 particle size distribution profile measurements in the North Atlantic [De Leeuw, 1986]. The calculated profiles were fitted to the experimental data at a height of 11 m above sea level. The agreement in this example is good for all particle sizes shown (17-37 μm), except in the lower 2 m. Here the predicted concentrations are higher than those observed, and the discrepancy increases as the particles become larger. This has also been found from comparisons of the model with other profiles. However, in most cases the agreement between model and experiment is worse than shown in Figure 3, in particular in high winds where the surface production rates are largely overestimated. Also at higher altitudes the model often fails. The results can be summarized as follows. In low winds the (quantitative) predictions by the model are correct for small particles, but not for particles larger than about 15-20 μm. In high winds the model fails also for the smaller particles.

The surface flux estimates are based on an exponential increase of the particle concentrations toward the sea surface. A compilation of experimental data supports this hypothesis (cf. Blanchard and Woodcock [1980]). However, the data were sampled under different conditions, at different places and with different techniques. The profiles used in the above intercomparison were measured in a time lapse of about one hour and revealed the occurrence of minima and maxima that were ascribed to the action of the wave-rotor mechanism (cf. De Leeuw, 1986]). Hence an exponential profile does not apply near the air-sea interface and the assumed surface flux profile relationship should be reformulated.

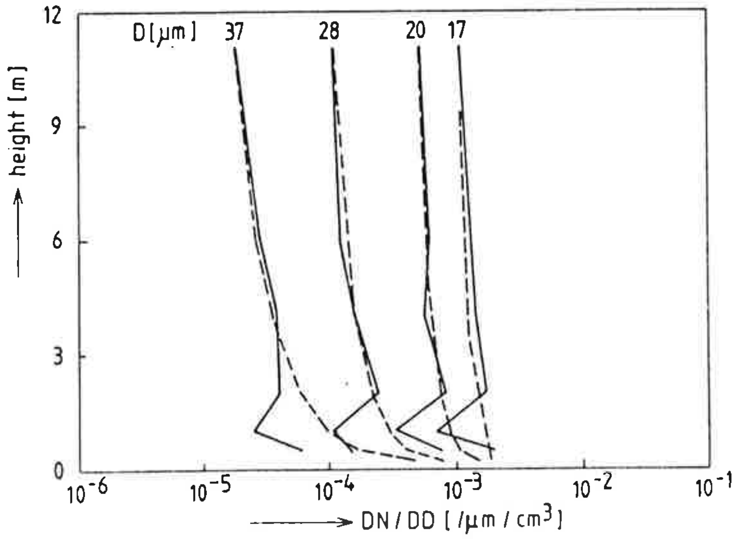

Figure 3. Comparison of calculated surface layer profiles (broken lines) with measured particle size distribution profiles. The theoretical profiles were fitted to the data at 11 m. Particle diameters are indicated on top of the curves.
Windspeed u = 9.8 m/s, RH = 67%, L = -162 m.

Discussion.

The dynamic behaviour of the atmospheric mixed-layer was monitored during the HEXMAX experiment by measuring aerosol backscatter profiles with a calibrated lidar system (wavelength 1.06 μm). Some representative results were presented, showing the variation of the mixed-layer height and the occurrence of layers and aerosol density variations. The application of lidar to verify a mixed-layer model for the aerosol vertical structure was discussed. The model takes humidity effects into account on both the fall velocities and the particle size distribution.

The good agreement between calculated and experimental profiles does not mean, however, that the model is also reliable in the surface layer. Measurements of particle size distribution profiles indicate that the particle concentration gradients near the sea surface are smaller than predicted by the model. In particular in high winds minima and maxima are observed in the particle concentration profiles [De Leeuw, 1986, 1988b] and the concentrations in the wave troughs may be higher than at the surface. To explain these results a wave-rotor model has been proposed [De Leeuw, 1986]. As discussed elsewhere [De Leeuw, 1988b, c], the competition should be considered between turbulent transport and the wave-rotor mechanism, while also production by the bubble mechanism and by wave disruption, as well as deposition of particles in the waves may affect the surface layer profiles in different ways.

Analysis of the HEXMAX data set, as well as data from other experiments, could yield more insight into the observed phenomena of aerosol dispersal and the influence of aerosols on the optical and meteorological parameters. Empirical models might become more reliable, while on the other hand the extensive data set will be used to improve knowledge on the physics involved in aerosol production and dispersal in the surface layer. A theoretical approach has been outlined in De Leeuw [1988c].

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