JP2.16 EVALUATING THE SEMI-DIRECT AEROSOL EFFECT: THINNING OF MARINE STRATOCUMULUS DUE TO ABSORPTION OF SOLAR RADIATION BY AEROSOL

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1. INTRODUCTION

Aerosols have an important role in climate change through their direct effect (scattering and absorption) and indirect effects (via changes in cloud microphysical properties) on the radiation budgets. Both direct and indirect effects are believed to have a negative radiative forcing that cools the climate system (IPCC, 2001). However, recent studies propose a semi-direct aerosol effect that has a positive radiative forcing (Hansen et al. 1997, Ackerman et al. 2000). Aerosols that contain dark material such as black (elemental) carbon heat the atmosphere through the absorption of solar radiation. This may lead to the evaporation of clouds and an increase in low level atmospheric stability, reducing surface moisture fluxes. Subsequent reductions of low cloud cover and Liquid Water Path (LWP) lead to a positive semi-direct radiative forcing.

The semi-direct aerosol effect was revealed by GCM experiments (Hansen et al., 1997). It was also investigated by Ackerman et al. (2000) using Large-Eddy-Simulations (LES) of trade wind cumulus with aerosols based on observations from the INDian Ocean Experiment (INDOEX). In this case the semi-direct aerosol effect was similar in magnitude (~ 3wm^{-2}) but has opposite sign to the direct aerosol effect. However, the magnitude of the semi-direct effect will depend not only on the aerosols present but also on the meteorology and cloud properties of a particular case. Here we investigate the semi-direct aerosol effect in a marine stratocumulus case using LES with idealised aerosol scenarios.

2. MARINE STRATOCUMULUS CASE

Marine stratocumulus form extensive sheets (106km^2) on the eastern side of ocean basins and have a strong influence on the earth's radiation budget, particularly by scattering solar radiation back to space. Stratocumulus form in shallow well-mixed boundary layers capped by a strong temperature inversion (Fig 1) and are sustained by turbulent moisture fluxes through the boundary layer. Turbulent mixing in the stratocumulus topped boundary layer is driven mainly by longwave cooling at the cloud top.

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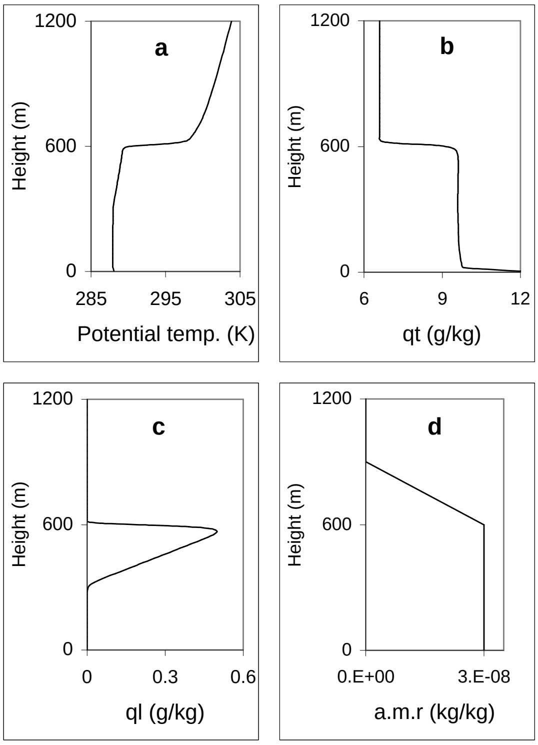

Fig 1: Horizontal averages of:
a) Potential temperature, b) total water mixing ratio, c) liquid water mixing ratio, at midnight of day 1, 18 hours into the control run.
d) Idealised vertical distribution of aerosol mixing ratio specified in all aerosol cases.

During the day absorption of solar radiation leads to a reduction in the generation of turbulence at cloud top and a stabilising of the boundary layer, which can decouple the cloud layer from the surface layer.
This reduces the moisture flux to the cloud and with further solar heating the cloud thins reaching a minimum LWP in the afternoon. During the night the cloud layer thickens as it cools and recouples with the surface layer. Using LES we evaluate the impact of absorbing aerosols on the diurnal cycle of LWP and radiative forcing.

3. EXPERIMENTAL SETUP

We use observations from the First International satellite cloud climatology project Regional Experiment (FIRE) (Hignett, 1991) to initialise the UK Met Office Large Eddy Model (LEM) (Gray and Petch, 2001) with a stratocumulus topped boundary layer.

The sea surface temperature is set to 288K and the large-scale subsidence rate, w, is given by w = D * Z, where D = 5.5 x 10^{-6} s^{-1}, and Z is altitude. The LES are initiated at 0600 local time on 15th July at latitude 33^0N and run for 42 hours. Four LES were run, each with different aerosol properties. The aerosol properties are based on an external mixture of ammonium sulphate with varying amounts of soot designed to give a realistic range of single scattering albedos (ω): 0.88, 0.92, 0.96 and 1.00, and a moderate optical depth of 0.1 at wavelength 0.55µm. The aerosol vertical distribution is based on the assumption that aerosols are confined mainly to the boundary layer (Fig 1d). There was also an aerosol free control run. The LES had a resolution of 50m in the horizontal and 80 levels in the vertical with a domain size of 2.5km x 2.5km except for the cases with ω = 0.92 and 0.96 which had a domain size of 1km x 1km due to constraints on computer time.

4. RESULTS

During the day the LWP reduces (Fig 2) due to the absorption of solar radiation. Most of the absorption takes place in the cloud layer leading to evaporation of the cloud and the stabilizing of the boundary layer, reducing the turbulent moisture flux into the cloud. Absorbing aerosols increased the solar absorption in the boundary layer from 63 to 85 Wm^{-2} at midday for the most absorbing aerosol case (ω=0.88). This increased the heating rate in the boundary layer by around 2.5Kday^{-1} at midday for the most absorbing case. Figure 2 shows that LWP falls about 20gm^{-2} lower in the most absorbing case compared to the aerosol-free control run. In both cases cloud cover remains 100% throughout the day but the difference in LWP leads to a reduction of cloud top albedo producing a semi-direct radiative forcing (Fig 3)

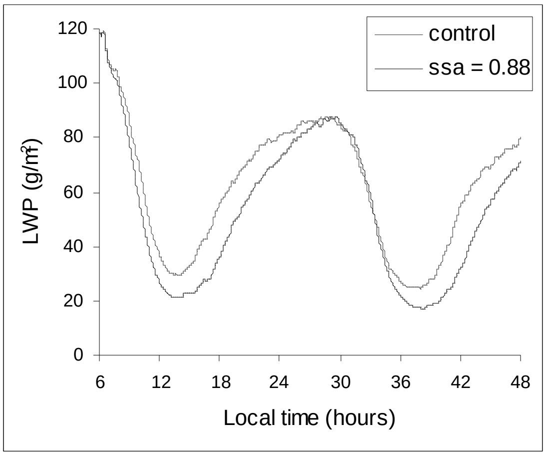

Fig 2: LWP as a function of local time. Thin line is the aerosol-free control run and thick line is the most absorbing aerosol case (ω = 0.88).

The semi-direct forcing is calculated by subtracting the direct aerosol forcing (change in net radiative flux at the Top Of the Atmosphere (TOA) due to scattering and absorption by aerosols) from the total aerosol forcing (difference in TOA net radiative flux between the aerosol cases and aerosol-free control run) including cloud response:

Semi-direct forcing = Total forcing - Direct forcing

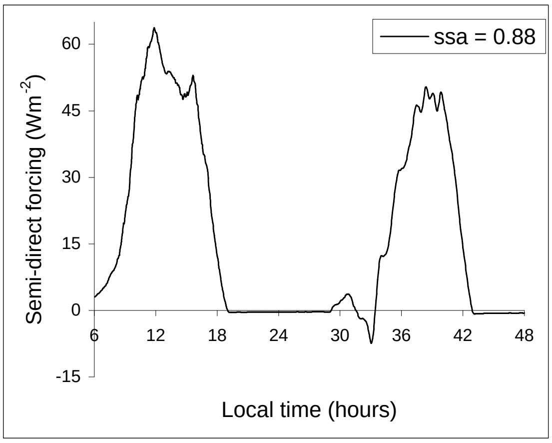

Fig 3: Semi-direct aerosol forcing as a function of local time for the most absorbing aerosol case (ω=0.88).

The radiative forcings are calculated for July 15-16th and at a latitude of 33^0N so are representative of the observation period and location, not an annual average.

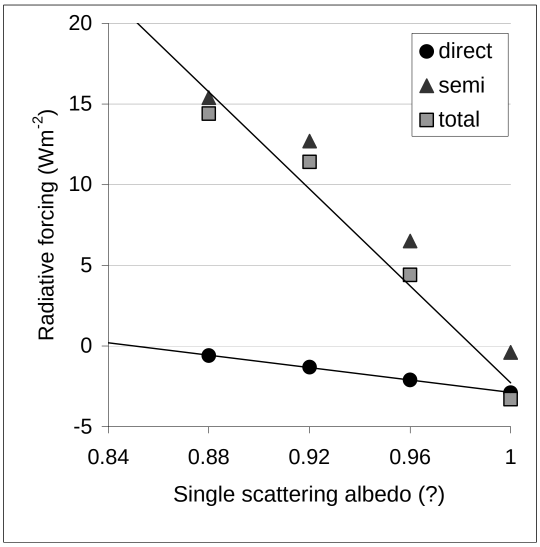

Fig 4: Diurnal average TOA aerosol radiative forcings as a function of aerosol ω with lines of linear regression for the direct and total forcings.

The direct radiative forcing is negative, due to aerosol scattering, for all aerosols in these simulations (ω > 0.88) but increases with absorption (1 - ω). At some lower value of ω the direct forcing would become zero when aerosol absorption and scattering would have equal and opposite effects, this is known as the critical single scattering albedo (ω^*). A linear regression estimates $\omega^* \sim 0.85$ for this experiment (Fig 4). The semi-direct forcing is roughly zero for the scattering aerosol case but increases with aerosol absorption (1 - ω) to 15.4 Wm^{-2} for $\omega = 0.88$. The total forcing is positive for all absorbing aerosol cases ($\omega <$ 0.96) because the semi-direct forcing offsets the (negative) direct forcing. A linear regression suggests that the total forcing would be zero for an aerosol ω of 0.985 (Fig 4). We can define this value of ω as an alternative critical single scattering albedo (ω^{**}) that depends on both the direct and semi-direct aerosol effects

5. CONCLUSIONS AND DISCUSSION

LES show that the absorbing aerosols lead to a reduction of LWP in the marine stratocumulus topped boundary layer. This reduction in LWP leads to a large positive semi-direct radiative forcing.

The semi-direct effect depends on the absorption of solar radiation by aerosols in the cloudy layer and is therefore proportional to the aerosol optical depth and co-albedo (1-ω) in that layer. We add aerosols to the boundary layer keeping optical depth fixed at 0.1 and vary the amount of aerosol absorption by varying aerosol ω. Even for the case with the weakly absorbing aerosols ($\omega = 0.96$) we find that the semi-direct aerosol effect is quite large (6.5 Wm^{-2}) and offsets the direct aerosol effect (-2.1 Wm^{-2}). A linear regression suggests that the total forcing (direct forcing + semi-direct forcing) will be positive for $\omega < \omega^{**} = 0.985$. The aerosol ω retrieved from field experiments in marine environments (e.g. INDOEX, ACE, ACE-ASIA, TARFOX) is often below 0.985 suggesting that the total aerosol forcing (neglecting indirect effects) would often be positive in marine stratocumulus situations.

We have not attempted to quantify the indirect aerosol effects; these may contribute a significant negative forcing. It is not possible to determine from these results whether the semi-direct aerosol effect is more or less important than the indirect aerosol effects. The relative sizes of the direct and semi-directs will depend greatly on the aerosol vertical distribution. Here we have used an idealised vertical distribution where aerosols are mainly in the boundary layer. However, the marine boundary layer can sometimes be quite clean with aerosol layers above (Jim Haywood, personal communication). In the case the semi-direct effect would be small but the direct effect can be strong. Furthermore the semi-direct aerosol effect depends on the meteorological scenario. Here we have only considered marine stratocumulus so it is not possible to make generalisations about the size or relative importance of the semi-direct aerosol effect on a global scale. This raises the need to understand and evaluate the semi-direct effect further, to establish whether it makes a significant global contribution to the radiative forcing of climate change.

6. REFERENCES

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