5.11 EFFECTS OF ARCTIC HAZE ON CLOUDS AND THE SURFACE RADIATION BALANCE

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1 INTRODUCTION

In the Arctic, concentrations of aerosols accumulate in winter and spring, reaching a maximum in April, dissipating by summer. It has long been recognized that high springtime aerosol concentrations, dubbed "Arctic Haze", are due to anthropogenic activities. More recently it has been suggested that Arctic Haze might alter the surface radiation balance by increasing cloud albedo (Twomey, 1991) and emissivity (Garrett et al., 2002). The latter effect may be particularly important during spring, when aerosol concentrations are high, clouds are sufficiently thin to be gray-bodies, and downwelling longwave flux dominates the surface radiation balance. Evaluating the effects of aerosols on downwelling surface flux during the Arctic spring is difficult since there exist very few *in situ* measurements during for this period. However, detailed surface sampling and remote sensing measurements at the North Slope of Alaska (NSA) CMDL and ARM laboratories near Barrow, Alaska may allow future investigation of this issue in the current absence of field programs.

2 CLOUD SUSCEPTIBILITY

For solar wavelengths, Twomey (1991) derived an expression for the "susceptibility" S_{SW} cloud albedo α to changes in droplet concentration N:

$$S_{SW} = \frac{d\alpha}{dN} = \frac{\alpha(1-\alpha)}{3N} \qquad (1)$$

Twomey showed that for the most pristine clouds (e.g. $N = 10\,cm^{-3}$), the addition of just one CCN per cubic centimeter can result in an increase in α by 1%. For arctic stratus during summer, values of S_{SW} range from $0.6 \times 10^{-3}\,cm^{-3}$ to $2.2 \times 10^{-3}\,cm^{-3}$ (Hegg et al., 1996).

In general the energy balance within a cloud is

$$\alpha + \varepsilon + t = 1 \qquad (2)$$

where, ε is the emissivity and t the transmittance of the layer. In the infrared, if multiple scattering is ignored (i.e. $\alpha = 0$), the emissivity can be approximated as

$$\varepsilon = 1 - \exp\left(-\beta Q_{abs} N \bar{r}^2 \Delta z\right) \qquad (3)$$

where, β is the diffusivity factor, Q_{abs} the absorption efficiency, and Δz the depth of the layer. βQ_{abs} increases nearly linearly with size in clouds with very small droplets ($\bar{r} \simeq 5\,\mu m$), but the dependence tapers rapidly as droplet size increases. In clean clouds with larger droplets, βQ_{abs} is nearly constant (Garrett et al., 2002). From (3), and assuming cloud LWP is constant, an analogous expression to (1) for cloud emissivity (S_{LW}) is

$$S_{LW} = \frac{d\varepsilon}{dN} = \frac{-(1-\varepsilon)\ln(1-\varepsilon)}{3N} \qquad (4)$$

Fig. 1 illustrates S_{LW} as a function of N and ε. S_{LW} reaches a maximum of $\simeq 1\%\,cm^{-3}$ in clean clouds with $N \simeq 10\,cm^{-3}$, and emissivities of $\simeq 0.6$. The most opaque and transparent clouds do not exhibit sensitivity to increases in droplet concentrations.

3 OBSERVATIONS

A NOAA CMDL laboratory, and an ARM remote sensing laboratory are located adjacent to one another at the NSA site near Barrow Alaska (71° N

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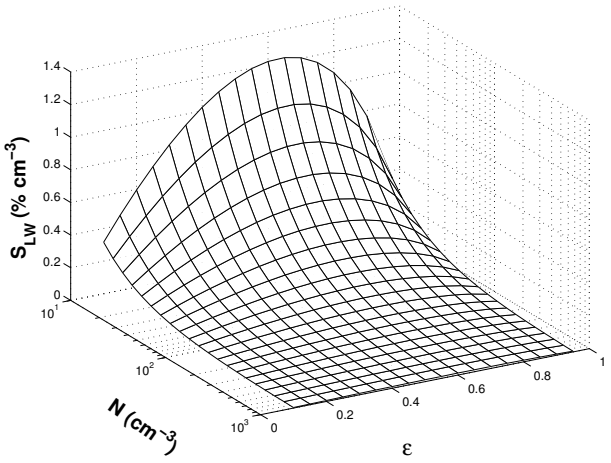

Figure 1: Susceptibility of cloud emissivity to changes in cloud droplet concentration.

157° W). NSA CMDL provides continuous measurements of aerosol properties. The NSA ARM site provides an extensive suite of radiometric measurements. Dong and Mace (2003) have used NSA ARM pyranometer, ceilometer, and radar data to retrieve the microphysical properties of arctic liquid water stratus clouds for the months May to September, 2000. They showed that monthly-averaged droplet concentrations are at a maximum in spring, and a minimum in summer. Droplet sizes were smallest in spring and highest in summer. Since this trend is consistent with the seasonal pattern of pollutant mass concentrations observed at CMDL (Quinn et al., 2002), these results suggest long-range seasonal transport of pollution to the Arctic might perturb the the microphysical properties of arctic clouds.

Arctic Haze events occur on time scales of a few days rather than the monthly averages reported by Quinn et al. and Dong and Mace. Ideally, high-frequency measurements of CCN should be used to compare surface aerosol measurements to retrieved cloud properties. *CCN* are not measured at CMDL. As a proxy we use aerosol scattering (σ_{sp}). σ_{sp} is a clear indicator of Arctic Haze, and aerosols with sizes between 0.1 and $1.0\,\mu m$ diameter, typical of CCN, are efficient (per unit mass) at scattering light. Therefore, to test whether cloud microphysics correlates with pollution events, we have plotted hourly-averaged σ_{sp} measured at CMDL versus Dong and Mace retrievals of N and r_e (Fig. 2). There is variability in the data, however, there is a clear linear correlation between σ_{sp} and N ($r = 0.61$), and an inverse correlation between σ_{sp} and r_e. If the hourly data are grouped into "polluted" ($\sigma_{sp} > 5\,Mm^{-1}$) and

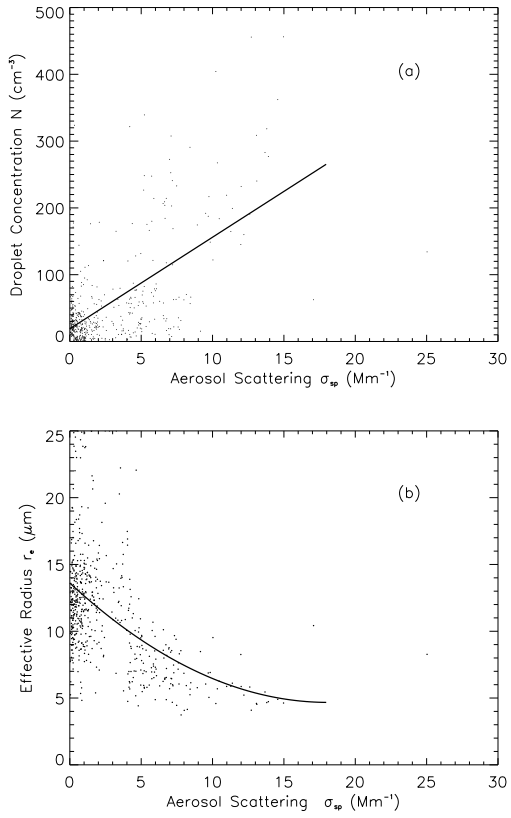

Figure 2: Scatter plot of droplet concentration (a) and effective radius (b) retrieved from ARM data at Barrow using the Dong and Mace (2003) algorithm, and the scattering coefficient measured at CMDL. Data represent one-hour averages between May and September 2000. The figures include first (a) and second-order (b) fits to the data.

"clean" ($\sigma_{sp} < 5\,Mm^{-1}$) events, the retrieved droplet effective radius is $7.1 \pm 1.9\,\mu m$ and $12.5 \pm 3.9\,\mu m$, respectively. The most polluted days occurred during May.

4 DISCUSSION

The co-location of the ARM and CMDL sites at Barrow can be exploited to investigate the relationship between pollution and stratus microphysics. Observations between May and September illustrate how long-range pollution to the Arctic in winter and spring might result in larger droplet concentrations and smaller droplets. The effect of pollution on so-

lar surface fluxes may be small since the arctic surface is usually bright, and pollution is at a minimum when the sun is up. However in winter and spring, arctic clouds are usually sufficiently thin to be graybodies (Hobbs and Rangno, 1998, Garrett et al., 2002), and cloud emissivity is susceptible to perturbations by anthropogenic aerosols. High values of cloud emissivity correspond with high downwelling longwave fluxes at the surface.

The Dong and Mace algorithm is currently being extended to years beyond 2000, and remote sensing algorithms are being developed to retrieve the microphysical properties of arctic clouds during the dark and twilight months. Based on these studies we aim to evaluate the effect of long-range pollution transport on the surface radiation balance of the arctic.

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