MICROPHYSICS OF PYROCUMULONIMBUS CLOUDS

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1. INTRODUCTION

The intense heat from forest fires can generate explosive deep convective cloud systems that inject pollutants to high altitudes. Both satellite and high-altitude aircraft measurements have documented cases in which these pyrocumulonimbus clouds inject large amounts of smoke well into the stratosphere (Fromm and Servranckx 2003; Jost et al. 2004). This smoke can remain in the stratosphere, be transported large distances, and affect lower stratospheric chemistry. In addition recent in situ measurements in pyrocumulus updrafts have shown that the high concentrations of smoke particles have significant impacts on cloud microphysical properties. Very high droplet number densities result in delayed precipitation and may enhance lightning (Andreae et al. 2004). Presumably, the smoke particles will also lead to changes in the properties of anvil cirrus produces by the deep convection, with resulting influences on cloud radiative forcing.

In situ sampling near the tops of mature pyrocumulonimbus is difficult due to the high altitude and violence of the storms. In this study, we use large eddy simulations (LES) with size-resolved microphysics to elucidate physical processes in pyrocumulonimbus clouds.

2. APPROACH

For this modeling study we use a 48-km square horizontal domain with uniform 500-m grid spacing. The vertical domain is 0–24 km with 375 km spacing. Boundary conditions are specified as rigid at the top and bottom and open at the horizontal faces. Cloud microphysical properties are treated with a size resolved scheme consisting of 32 size bins each for aerosols, droplets, and ice crystals spanning 5 nm–1 μm, 2 μm–1 cm, and 2 μm–3 cm, respectively. Algorithms used for processes such as nucleation, condensational growth, aggregation, breakup, and sedimentation are described by (Fridlind et al. 2004).

We focus here on the pyrocumulonimbus cloud system formed over the the Chisholm fire that occurred 28 May, 2001, in Alberta, Canada. Results

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from this case will be compared with simulations of pyrocumulus observed during the LBA-SMOCC campaign in Brazil. (Fromm and Servranckx 2003) documented the injection of large smoke cloud deep into the stratosphere by supercell convection associated with the Chisholm fire. Following (Winterrath et al. 2003), we specify the fire as a 10-km by 500-m source of heat, smoke particles, and water vapor, with fluxes of 300 kJ m^{-2} s^{-1}, 18.9 g H_2O m^{-2} s^{-1} and 100 CN/cm^{-2} s^{-1}, respectively. We use a nearby pre-storm sounding with a convective available potential energy (CAPE) of 350 J kg^{-1}. The thermodynamic instability in this case was clearly insufficient to generate a severe storm without heat input from the fire.

We describe below the overall evolution of the pyrocumulonimbus in the baseline simulation described above. Several sensitivity tests have been run to evaluate the importance of the different fire fluxes on the cloud evolution. We focus on the fire aerosol input impact on pyrocumulus processes and the resulting anvil properties.

3. RESULTS

The strong heat source specified drives a rapid buildup of explosive convection. Within 20 minutes, the peak updraft speeds exceed 40 m s^{-1}. Figure 1 shows a cross section of the storm perpendicular to the fire line at 50 minutes into the baseline simulation. The convection penetrates the tropopause (about 12 km) and injects large amounts of ice into the stratosphere up to as high as about 14 km.

Figure 2 shows the evolution of various cloud-system diagnostics for the baseline simulation and sensitivity tests with the fire water vapor and aerosol sources removed. For this pyrocumulonimbus case, the heat source from the fire dominates the dynamical evolution and bulk properties of the cloud. The source of water vapor from the fire does not change the cloud dynamics and increases the cloud ice water path (IWP) by only about a 25%. Similarly, the large source of smoke particles acting as CCN have no impact on the cloud dynamics and only minimal impact on LWP or IWP. How-
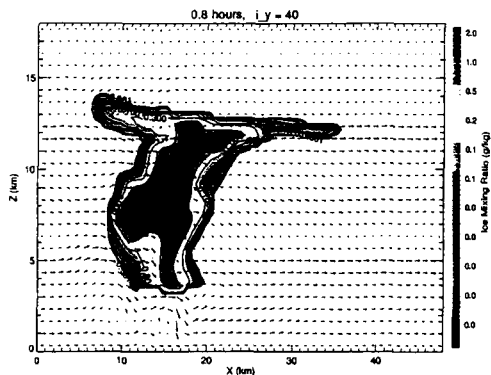
Figure 1: Condensed water content (g kg^{-1}) is plotted for on an x-z plane through the center of the model (perpendicular to the fire line) at 50 minutes into the baseline simulation.

Figure 2: The evolution of maximum vertical wind speed, liquid water path (g m^{-2}), ice water path (g m^{-2}), anvil ice crystal concentration (cm^{-3}), and maximum precipitation rate (mm hr^{-1}). The water vapor source has very little effect on the cloud simulation. The fire aerosol source (smoke particles) has little impact on the bulk cloud properties or dynamics, but the anvil cirrus microphysical properties are strongly altered by the smoke particles

ever, the smoke particles and water vapor source dramatically change the cloud microphysical properties. Peak ice concentrations increase by about an order of magnitude from $\simeq 20$ cm^{-3} in the case with no smoke to $\simeq 200$ cm^{-3} in the baseline simulation with the smoke particle source. Excluding the water vapor source reduces peak ice concentrations by about a factor of 5 compared to the baseline simulation.

Unexpectedly, neither the timing of precipitation onset or the magnitude of precipitation are substantially affected by the numerous smoke particles acting as CCN in the pyrocb. Precipitation is delayed only very slightly, and the cumulative precipitation is reduced by no more than about 50In analysis of pyrocumulus clouds over the Amazon, (Andreae et al. 2004) showed that warm rain was significantly delayed and reduced by biomass burning aerosols. The increase in droplet concentration limited droplet sizes and prevented precipitation development until ice formed in the updrafts. This effect is less important for the boreal Chisholm fire for two reasons: (1) The surface is much colder at high latitudes than in the tropics so the freezing level, 0°C, is reached at a lower altitude (about 3.2 km for the Chisholm case versus about 5 km in the deep tropics); (2) given the very strong updrafts in this pyrocb ($\simeq 40$ m s^{-1}), the freezing level is reached within the updraft within 15 minutes, so precipitation associated with the ice phase occurs very quickly anyway.

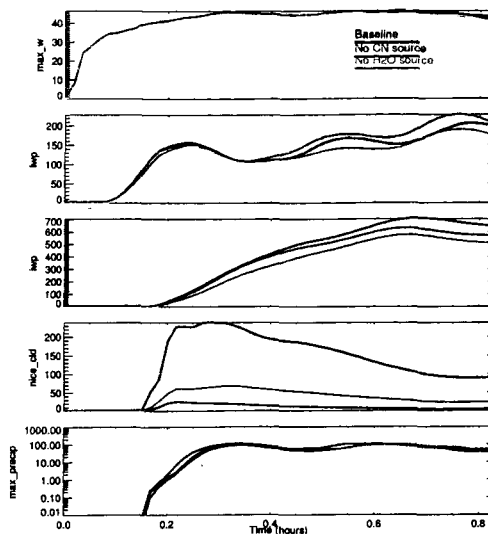The anvil ice crystal size distributions (Figure 3) are also dramatically altered by the fire particle and water vapor sources. With all of the fire fluxes included (baseline case), anvil ice concentration is dominated by crystals smaller than 10 μm radius. Eliminating either the H$_2$O or particle source results in more than an order of magnitude reduction in average anvil ice concentration, and omitting the particle source increases the ice mode radius from $\simeq 6$ μm to $\simeq 18$ μm. In the baseline pyrocb simulation, the anvil crystals are significantly smaller than those observed in typical cumulonimbus anvils (Garrett et al. 2003).

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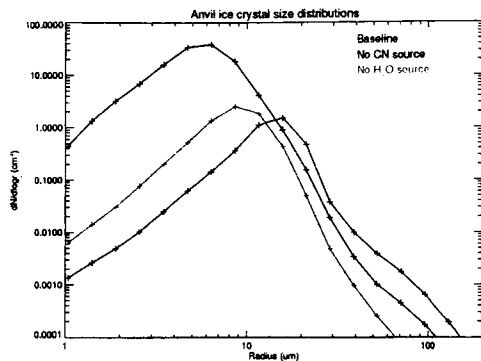
Figure 3: Horizontally averaged anvil ice crystal size distributions are plotted. We have excluded grid boxes with vertical wind speeds larger than 2 m s^{-1}.

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