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A THEORETICAL STUDY OF THE IMPACT OF BIOMASS-BURNING CCN ON THE DYNAMICS OF DEEP CONVECTIVE CLOUDS WITH MIXED PHASE

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1. INTRODUCTION

Clouds are important components of the climate system as they affect the Earth's albedo and they participate in the hydrological cycle. One of the largest uncertainties in climate modeling is related to the parameterization of convective processes and, in particular, the question of how anthropogenic emissions may affect the different types of clouds is still open. Most research has been devoted to warm stratocumulus clouds, and only recently some studies incorporate changes in cirrus and mixed phase clouds. Emissions of gases and particles during biomass burning may affect the microphysics and dynamics of clouds developing near and downwind of said emissions, and some studies have suggested that precipitation may be inhibited (Ramanathan et al, 2001). Nevertheless, there have not been many studies that explore the effect that cloud condensation nuclei (CCN) originated by biomass burning may have on deep convective clouds, in which the ice phase is dominant.

In this study we have introduced changes in the parameterization of the autoconversion and accretion processes in a 3-dimensional numerical model to represent the increased ambient CCN and evaluate the dynamical response and the evolution and magnitude of precipitation.

2. THE MODEL

We used the numerical model Advanced Regional Prediction System (ARPS, Version 4.5.1), a 3-dimensional, non-hydrostatic, compressible model valid for scales from a few meters to hundreds of kilometers (Xue et al. 1995). ARPS was developed at the Center for the Analysis and Prediction of Storms, University of Oklahoma and has been used in a variety of numerical studies (Xue et al., 1996; Fovell and Tan, 1998, Xue et al. 2001, 2002, 2003).

The bulk microphysical parameterizations in the model are based on Kessler (1969) for liquid phase and Lin et al. (1983) for solid and mixed phase processes. The later includes a modification of Berry's (1967) parameterization for rain autoconversion. We have modified these parameterizations in order to incorporate the effect of increased ambient CCN and therefore, activated droplets.

The first step was to modify only the warm rain processes. The methodology proposed by Liu and Daum (2004), based on gamma functions for the cloud droplet distributions, was incorporated. Since the main goal was to study the response of mixed-phase, deep clouds to enhanced ambient CCN, the second step involved modifications in the cold-rain subroutines as well.

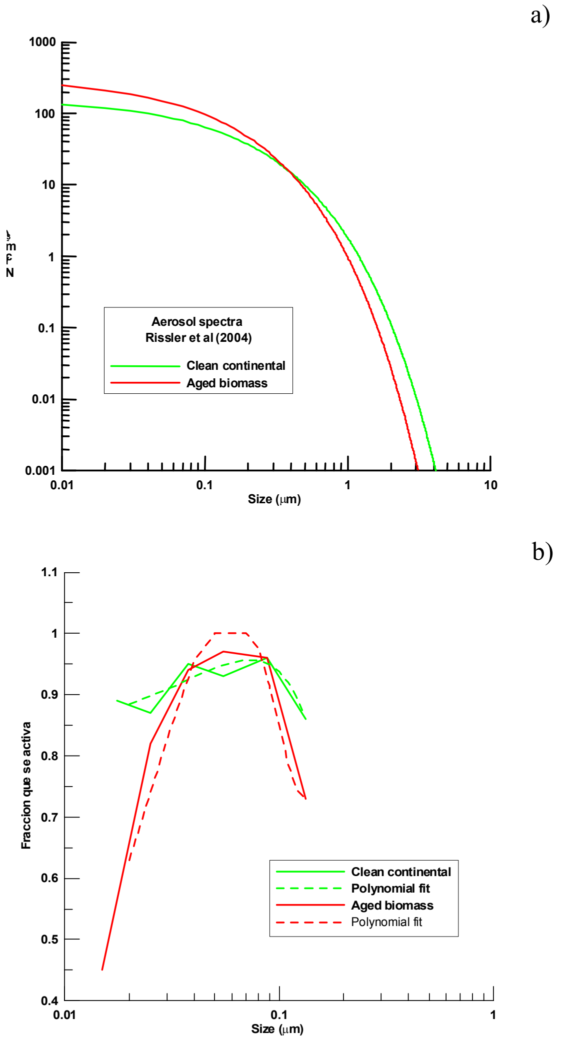

Figure 1. a) Aerosol number distributions and b) activation fraction, for the clean continental (green) and aged biomass (red) cases.

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The parameters in the gamma distribution are obtained from observations made at the surface in the regions of Amazonia and Rondonia, in Brazil. Rissler et al (2004) present results from aerosol size distributions and activation fractions, for clean and polluted cases. The polluted cases include both measurements close to the sources as well as aged aerosol. We have selected the latter, since the clouds that we simulated were located several hundred kilometers downwind of the biomass burning regions. Figure 1. a) shows the two aerosol number distributions considered, while Fig 1b presents the activated fraction and the fits that were used in the simulations. Note that for intermediate particle sizes, the activation fraction is about 90% both in the clean and polluted cases, while it drops down to 45% for the smallest sizes in the polluted case (where the largest number concentrations are observed). We further assume that all the CCN activate at cloud-base and that the newly activated droplet size distribution does not change with height nor with time. Figure 2 presents the droplet size distributions in the two cases considered, where it can be seen that even though the total number of droplets is different (1986 vs 2332 per cc), the droplet spectra are not significantly different for droplets larger than 20 μm.

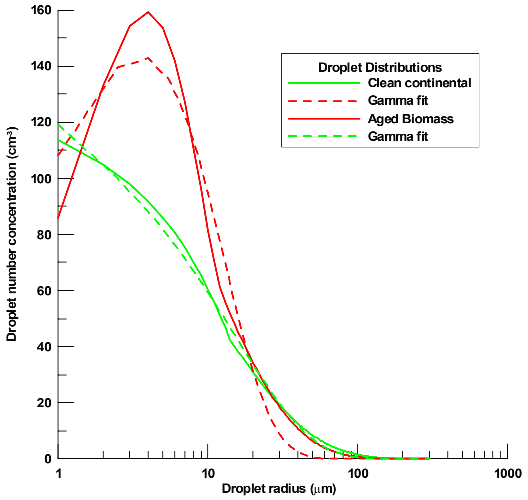

Figure 2. Cloud droplet number distributions for clean continental (green) and aged biomass (red) cases.

The cloud droplet size distribution for small droplets up to 100 μm in radius, considered in variable q_c (cloud water mixing ratio) is assumed to remain invariant even though the autoconversion process is active. Furthermore, these small droplets are assumed to have non-significant fall velocity and be carried with the flow. Larger droplets are considered part of variable q_r (rain water mixing ratio), with significant fall velocity.

A series of simulations was performed with the new autoconversion parameterization. We further tested the sensibility of the model to different values of the efficiency in the accretion process (from $E_{acc} = 1$ which is usually the default, down to $E_{acc} = 0.08$).

3. CASE STUDY: 28 APRIL 1982

The first case study selected corresponds to a very severe storm that developed a tornado in the city of Resistencia (in northern Argentina) and has been studied by Torres-Brizuela (2005). The model ARPS was successful in simulating the evolution of the storm, even reproducing the tornadogenesis phase..

The CCN used in the model were obtained from literature, and correspond to experimental studies in the Amazonia/Rondonia regions of recent and aged particles. ARPS was run on thermodynamic conditions representative of Northeastern Argentina during November, hundreds of kilometers away form the CCN sources. The environmental conditions were obviously very unstable (CAPE = 3584 J/K), and a small temperature bubble was used to initiate convection in a uniform background (based on the observed sounding from Resistencia).

4. RESULTS

a) Warm simulation

The modifications introduced in the model was expected to cause primarily a response on the warm rain process, therefore we first run a simulation with only those processes. Figures 3a and 3b show the evolution of the maximum cloud and rain water mixing ratios, respectively, compared with the control case (using the default Kessler parameterization in ARPS). As seen in the figures, the magnitude of the mixing ratios using the control parameterization results in significantly decreased concentrations in the initial times, while after an hour, the modified runs (both clean and polluted cases) are again in agreement with the control case. The explanation for this can be found in the different behavior of the individual terms representing the autoconversion and accretion processes. The modification introduced in the autoconversion scheme translates into a delay in the onset of autoconversion, from 500 s (in the control case) to over 1000 s into the simulation, which leads to a significant accumulation of cloud water mixing ratio in the modified cases. In agreement with this result, the production of the rain water mixing ratio (Fig. 3b) is also delayed by about 500 s in the modified runs, compared to the control case, with a slight further delay observed in the polluted case. In this warm simulation, the higher cloud water mixing ratio in the polluted case leads to a slightly higher rain water mixing ratio, due to a higher accretion than in the clean case, as seen in Fig. 4a and b. But overall, there is only minimal difference between the clean and polluted cases in terms of the domain-maximum magnitudes.

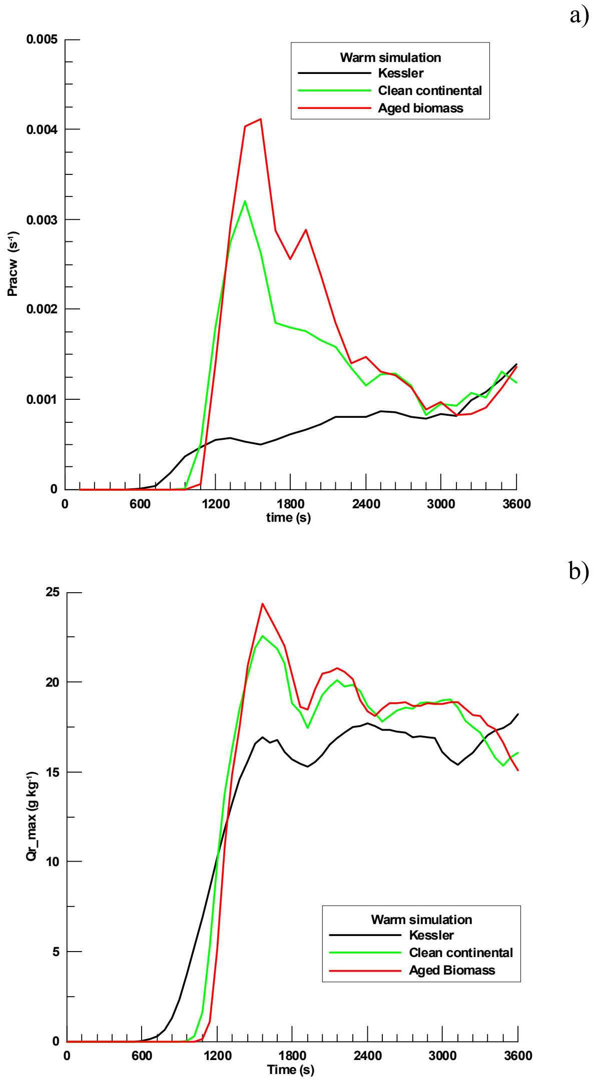

Figure 3. Time evolution of domain-maximum a) cloud water mixing ratio and b) rain water mixing ratio, for the clean continental (green) and aged biomass (red) cases, and the control run with Kessler (black).

Note that the autoconversion term in the control run continues to increase throughout the simulation, while the modified scheme leads to an initial maximum and the a substantial decrease in the clean case (about a factor of 4 decrease), while in the polluted case the autoconversion becomes zero after 2000 s into the simulation.

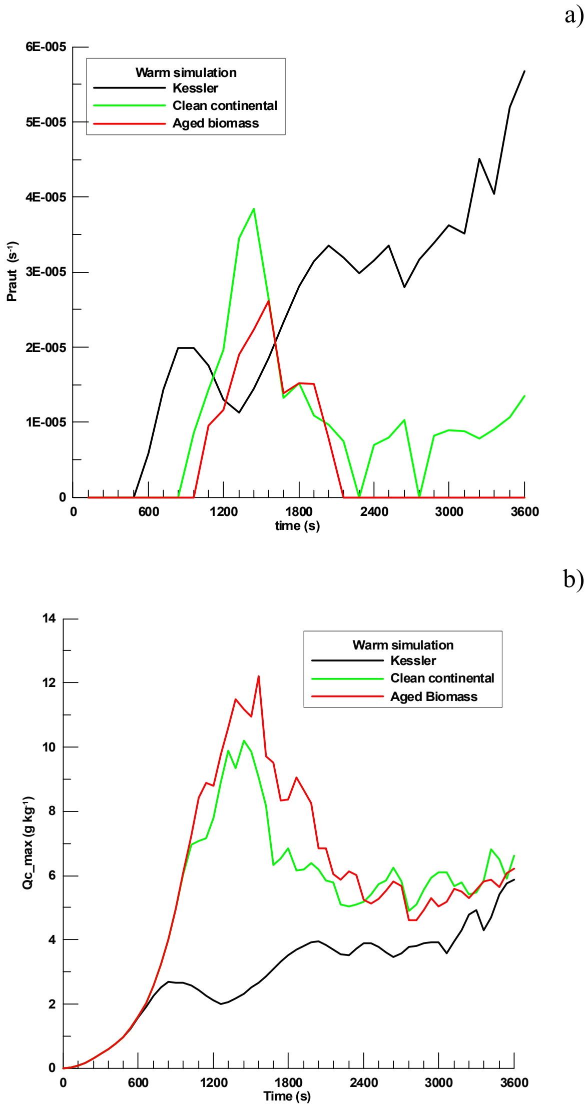

Figure 4. Time evolution of maximum a) autoconversion and b) accretion, for the clean continental (green) and aged biomass (red) cases, and the control run with Kessler (black).

These peaks in the autoconversion are responsible for the large cloud water mixing ratios in the modified scheme, which in turn lead to very large accretion rates that result in larger rain water mixing ratios than in the control run. Even though these large differences are observed in cloud and rain water mixing ratios, it should be pointed out the overall dynamical structure of the storm was unmodified, in these warm simulations.

b) Mixed phase simulation

The cold microphysics parameterization in ARPS, based on Lin et al (1983) was also modified, so the autoconversion process is sensitive to the presence of ambient CCN. Simulations were also performed for different values of the parameter that represents the efficiency of accretion. Figure 5 presents the time evolution of the mixing ratio of all the hydrometeors simulated: cloud water, rain water, ice water, hail and snow, for the control run. Note that the solid phase is present from 600 s into the simulation, and the maximum hail mixing ratio is actually observed before the maximum rain water mixing ratio, which indicates that the rain is produced primarily by melting of hail and not by accretion of cloud water mixing ratio.

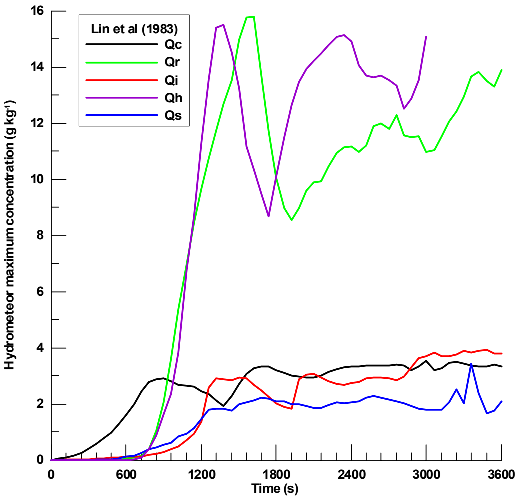

Figure 5. Time evolution of the mixing ratio of all the hydrometeors simulated in the control run with Lin et al (1983). Qc: cloud water; Qr: rain water; Qi: ice water; Qh: hail; Qs: snow.

Figure 6 presents the time evolution of the maximum cloud water mixing ratio for a several of the simulations performed, showing the clean cases in green, the polluted cases in red and the control run in dashed black. Note that all modified runs result in higher mixing ratios than the control run. The clean and polluted cases for each value of the accretion efficiency are virtually undistinguishable, suggesting a null sensibility to the initial CCN concentrations, and to the working hypothesis of this study.

Figure 7 presents the corresponding results for the time evolution of the maximum rain water mixing ratio for a several of the simulations performed, showing the clean cases in green, the polluted cases in red and the control run in dashed black. Note that again there is little difference between the simulations, particularly when the accretion efficiency is take to be 1.

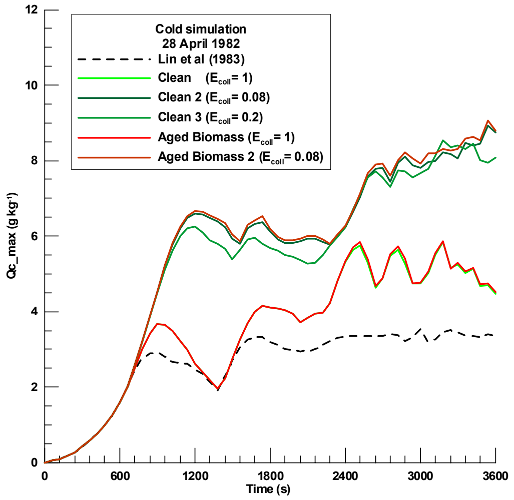

Figure 6. Time evolution of the cloud water mixing ratio simulated for several clean and polluted cases as well as in the control run (Lin et al ,1983).

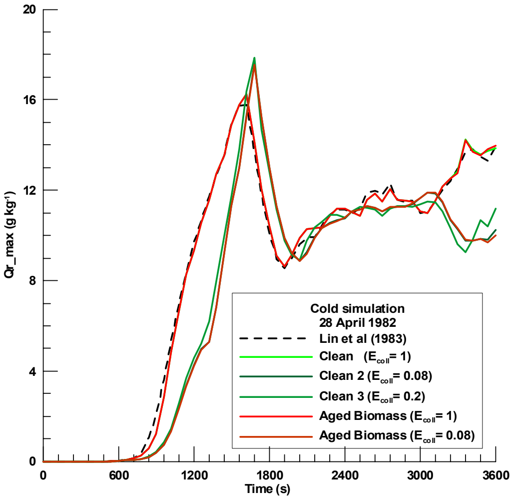

Figure 7. Time evolution of the rain water mixing ratio simulated for several clean and polluted cases as well as in the control run (Lin et al ,1983).

Remember that the modified scheme only changes the autoconversion process. A reduction in the accretion efficiency leads to a delay in the onset of the rain water mixing ratio, by only a few seconds, while showing no response to the initial CCN-cloud droplet concentration. This result indicates that the working hypothesis is not proven. It appears that the initial premise that more environmental CCN due to biomass burning would lead to a delay in the formation of precipitation and would lead to a decrease in the rain water mixing ratio, was not observed in the simulations. The thermodynamic and wind shear in the sounding used to initialize the simulations results in very strong convection, with up to 40 m/s updrafts that carry all the cloud water mixing ratio to very high regions where the cold microphysical processes dominate the production of the rain that reaches the surface. The large instability present in the environment with which the convection was initiated appears to be more important than the sensitivity to the ambient CCN concentration.

In order to evaluate the sensitivity of our results to environmental conditions, a case of more moderate CAPE (1490 J/K) observed on 20 January 2003 during SALLJEX (Vera, 2004) was also simulated. Figure 8 presents the time evolution of all hydrometeors for the control run (Fig 8a) and the modified clean case (Fig. 8b). In this more moderate convective case, the warm rain processes are able to dominate for a few minutes, resulting in the conversion of cloud water to rain water mixing ratio.

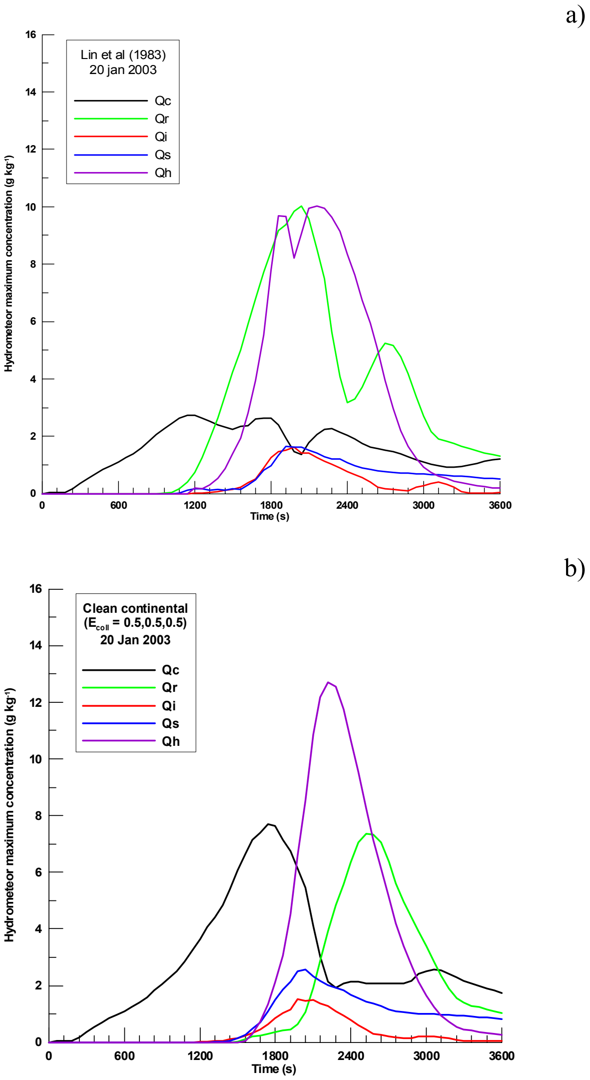

Figure 8. Time evolution of the mixing ratio of all the hydrometeors simulated in a) the control run with Lin et al (1983) and b) modified clean case.

Note that the maximum cloud water mixing ratio in the control case (Fig. 8a) is only about 2 g/kg, while in the clean modified case it reaches more than 7 g/kg (Fig. 8b). In the control case rain water is converted to hail. Note that in the modified simulation, the delay in the autoconversion leads to a change in the order of the processes that lead to rain water. In the modified case, it is the enhanced cloud water mixing ratio that is carried up to the cold regions in the cloud and then leads to the production of hail, which is now in substantially higher concentration than in the control run. The subsequent melting of hail leads to rain water in the modified case.

This more moderate CAPE case shows sensitivity in the order of the microphysical processes that lead to rain water mixing ratio, to a change in the autoconversion scheme.

5. CONCLUSIONS

This study was designed to evaluate the response of deep convection, with mixed phase, to the presence of enhanced ambient CCN concentration due to aged biomass emissions. A modified scheme was introduced in ARPS to account for the presence of enhanced cloud droplet concentrations in the autoconversion scheme.

The results suggest that when the atmospheric conditions are very unstable (leading to very deep convection, even in cases, to the occurrence of tornadoes), the autoconversion and accretion processes are not significant in changing the overall cloud dynamics, neither the total precipitation at the surface. These results indicate that the dynamics of the deep, mixed phase clouds simulated is not sensitive to the input of large concentrations of CCN originated during biomass burning. These results are very important, indicating that it is the interplay of the thermodynamic, dynamic (in terms of environmental shear) and microphysical processes what will determine the response of the deep convective clouds to enhanced ambient CCN. The answer to our initial hypothesis: aged CCN from biomass burning would lead to a decrease in precipitation, turned out to be much more subtle than expected, highlighting the complexity of the non-linear effects that are involved in mixed-phase convection. Further tests will be carried out in the future and will involve representing in the model the potential changes in the ice nuclei due to biomass burning.

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References

Fovell, R. G., and P.-H. Tan, 1998: The temporal behavior of numerically simulated multicell-type storms. Part II: The convective cell life cycle and cell regeneration. Monthly Weather Review, v. 126, p. 551-577.

Kessler, E., 1969: On the distribution and continuity of water substance in atmospheric circulation. *Meteorol. Monogr*. 10.

Lin, Y. L., Farley, R. D., and Orville, H. D., 1983: Bulk parameterization of the snow field in a cloud model. *J. Clim. Appl. Meteor*., 22, 1065-1092.

Liu, Y and P.H. Daum, 2004: Parameterization of the autoconversion process. Part I: Analytical formulation of the Kessler-type parameterizations. J. Atmos. Sci., 61, 1539-1548.

Ramanathan, V, P. Crutze, J. Kiehl and D. Rosenfeld, 2001: Aerosols, climate and the hydrological cycle. *Science*, 294, 2119-2124.

Rissler,J., E. Swietlicki, J. Zhou, G. Roberts, M. Andreae, L. Gatti and P. Artaxo, 2004: Physical properties of the sub-micrometer aerosol over the Amazon rain forest during the wet-to-dry transition – comparison of modelled and measured CCN concentrations. Atmos. Chem. Phys., 4, 2119-2143.

Torres-Brizuela, M. M., 2005: Simulación de tormentas convectivas severas en el entorno de Resistencia con un modelo numérico. Numerical simulation of convective severe storms around the area of Resistencia. Doctoral thesis, Dept. of Atmospheric Sciences, University of Buenos Aires, Argentina, 242 pp.

Vera, C, 2004: Introduction to the South-American Low Level Jet Experiment (SALLJEX). CLIVAR Exchanges, Vol. 9-1, 3-4.

Xue, M., K.K. Droegemeier, V. Wong, A. Shapiro and K. Brewster. 1995: ARPS Version 4.0 User's Guide. Available from Center for Analysis and Prediction of Storms, University of Oklahoma, Norman OK 73072. 380pp.

Xue, M., K.K. Droegemeier, D. Wang, and K. Brewster, 1996: Prediction and simulation of a multiple squall line case during VORTEX-95. Preprint: 18th Conf. on Severe Local Storms, 19-23 Feb., Amer. Meteor. Soc., San Franciscon, CA.

Xue, M., K. K. Droegemeier, and V. Wong, 2000: The Advanced Regional Prediction System (ARPS) - A multiscale nonhydrostatic atmospheric simulation and prediction tool. Part I: Model dynamics and verification. Meteor. Atmos. Physics., 75, 161-193.

Xue, M., K. K. Droegemeier, V. Wong, A. Shapiro, K. Brewster, F. Carr, D. Weber, Y. Liu, and D.-H. Wang, 2001: The Advanced Regional Prediction System (ARPS) - A multiscale nonhydrostatic atmospheric simulation and prediction tool. Part II: Model physics and applications. Meteor. Atmos. Physics., 76, 134-165.

Xue, M., D.-H. Wang, J.-D. Gao, K. Brewster, and K. K. Droegemeier, 2003: The Advanced Regional Prediction System (ARPS), storm-scale numerical weather prediction and data assimilation. Meteor. Atmos. Physics, 82, 139-170.