Simulating Arctic mixed-phase clouds:

Sensitivity to ice initiation mechanisms

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Motivation

The impacts of Arctic mixed-phase clouds on climate in terms of changes in surface radiative budgets remain uncertain due to the complexities in representation of mixed-phase clouds. The environmental conditions that determine Arctic cloud properties need to be thoroughly analyzed to fully represent these clouds in climate models. To evaluate the impact of ice initiation mechanisms on cloud glaciation time and develop a simplified bulk microphysics scheme for use in GCMs we use a modified version of the GISS SCM initialized with data from the DOE Arctic mixed-phase cloud campaign (M-PACE).

Model

The modified GISS SCM microphysical package includes 3 different cloud schemes: 1) routinely used in the GISS GCM original cloud scheme (Del Genio et al. 1996, J. Clim.) -- does not permit coexistence of liquid & ice phases; 2) two-moment bulk scheme (BLK), -- activation of liquid phase is permitted in environment under-saturated w.r.t water, parameterized using large-scale and sub-grid vertical velocities, divergence of radiative heat flux, and prescribed conc. of cloud condensation nuclei (CCN) with different chemical composition (Morrsion et al. 2005, JAS), and 3) a bin-resolved cloud scheme (BRM), -- spectrum of newborn cloud droplets calculated using balance equation for CCN, which can be of different chemical composition and can change in space and time, analytical solution for supersaturation (SS) eqns., and Koehler theory (Khain & Sednev 1996, Atmos. Res.).

Model set up and sensitivity experiments

The initial vertical profile used to drive SCM (36 levels with ~25 mb resolution near the surface) are given by idealized vertical profiles from observation during MPACE (Klein et al 2006). Large-scale forcing, subsidence velocity, and surface pressure, temperature, and fluxes are defined by ARM CMWG for model intercomparison. We focus on Period B (17Z October 9 to 5Z October 10) when single layer mixed-phase clouds with temperatures varying between -5C and -20C were observed. For our 12 hour runs we use BRM scheme with a 10 s time step. Microphysical data used to initialize BRM is in Fig. 1. Initially only liquid phase is present.

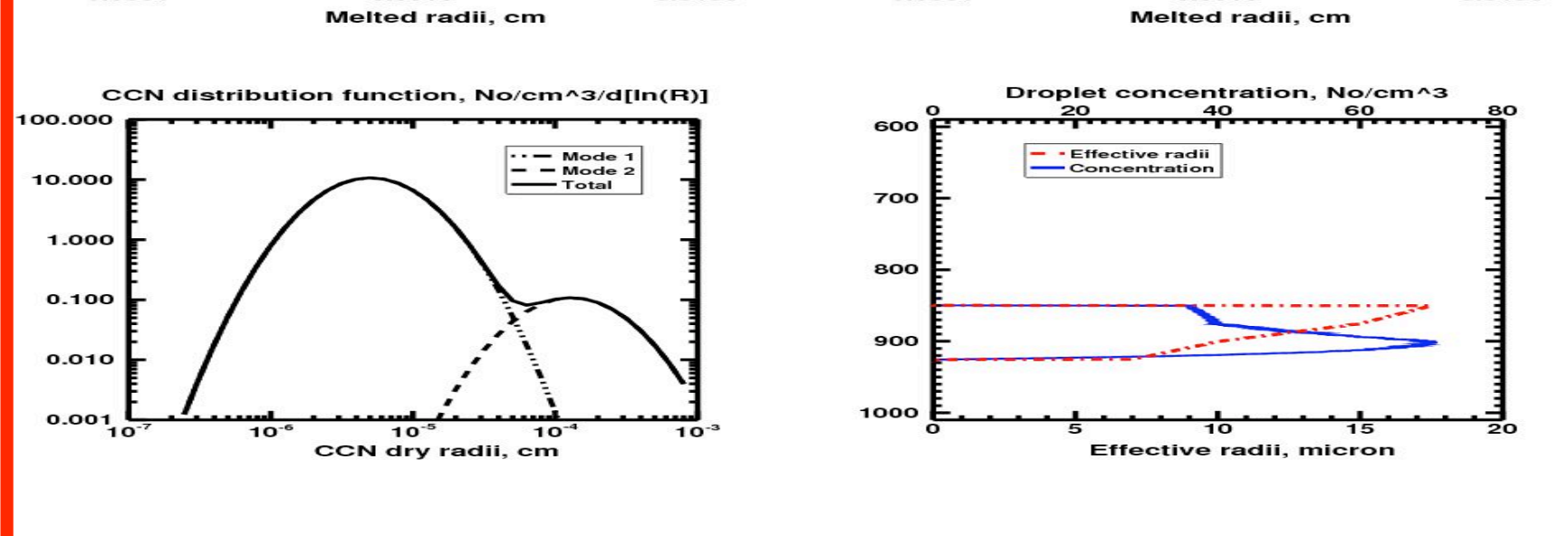

Fig. 1. Droplet mass and number distribution functions, CCN distribution function, vertical profiles of droplets concentration and effective radius.

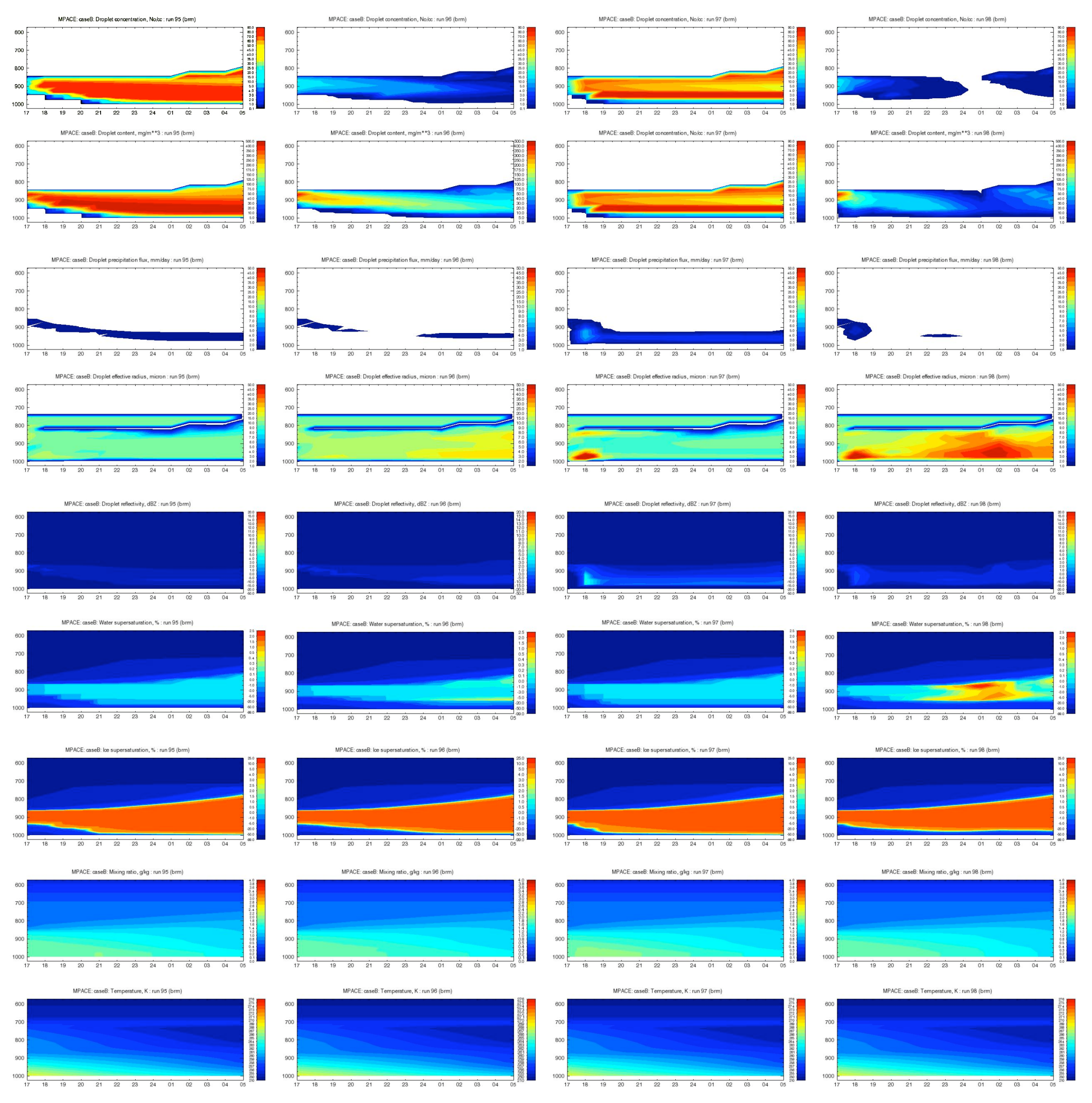

Fig. 2 Droplet conc., content, precipitation flux, effective radius, and radar reflectivity as well as SS w.r.t. water/ice, water vapor mixing ratio and temperature (top to bottom) in E95, E96, E97, and E98 (left to right).

Sensitivity runs with warm microphysics

To evaluate the impact of idealized forcing on modeled SS and importance of CCN spectrum shape that is initially independent of altitude, for drop activation, we perform a set of runs E95-E98, w/o ice microphysics. The remarkable feature of BRM droplets activation scheme is sensitivity to modeled SS that determines critical CCN radius, which is cut off radius for CCN spectrum, and number of droplets just nucleated. Cloud and thermodynamics characteristics in these experiments are in Fig.2 and in Table 1. In E96 (coagulation is switched off) droplet activation at particular level mainly occurs when SS exceeds its values in the previous time steps. Implied large-scale tendencies of temperature and wv mixing ratio together with prescribed subsidence velocity determine mainly negative tendencies of SS w.r.t. water in cloudy regions. These SS tendencies, turbulence, and radiation are balanced such that SS w.r.t. water rarely increases, and critical SS and CCN critical radius remain practically unchanged. This means that amount of water droplets just activated is negligibly small, and droplets conc. and content diminish with time due to evaporation at all levels during the first 6 hours in E96. After this time, in sub-cloud layers SS w.r.t. water becomes +ve due to instantaneous vapor supply from the surface and droplet evaporation just below initial cloud base. Starting with the lowest layer and propagating upward, SS remains +ve determining existence of non-dissipated warm clouds near the surface. Effective drop radii (Re) in these clouds reach ~ 25 micron in E96. If coagulation is active (E98) the process of rebuilding SS starts early, and SS reaches very high values ~3.5% because coagulation effectively reduce droplets conc. To prevent unrealistically high values of SS and very short glaciation time in experiments with ice microphysics, we update CCN spectrum after each time step with its initial values assuming that air masses with the same aerosol properties travel through the computational domain. Results of runs using this assumption for warm microphysics E95 and E97 (with coagulation) are in Fig. 2.

Sensitivity runs with ice microphysics

We consider 2 mechanisms of ice initiation. Their chief feature is involvement of liquid phase in ice initiation process (IIP). If liquid phase is not involved in IIP, we parameterize nucleation of ice crystals from wv as a func. of SS w.r.t. ice (Meyers et al 1992, JAM). It is assumed that this function determines the max. conc. of ice crystals which can be nucleated at a particular point. For a certain conc. of ice particles in the point, only the number of crystals needed to reach the conc. that is determined by this func. is nucleated. We assume that all newborn ice crystals, whose shape (plates, columns, or dendrites) depends on temperature, have the minimal size permitted by mass grid. This process operates for temperatures < -2C. When liquid phase is involved in IIP, ice nucleation is considered to proceed via drop freezing (Alheit et al 1990, JAS), and its rate is function of the shape of droplet distribution, water droplets mass and temperature. Newborn ice crystals of different sizes are assumed to be plate-like crystals. This process is active at -ve temperatures in both saturated and under-saturated w.r.t. water. Implied forcing assures existence of high SS w.r.t. ice (~20%), and crystals grow rapidly due to deposition and Bergeron-Fendeisen process. In all runs with ice microphysics (E90, E92-E94) we restore CCN spectrum to its initial values to prevent cloud glaciating in unrealistic short time. Cloud characteristics in these experiments are in Fig. 3 and Table 1.

In E92 (only the first IIP is active with the constant in Meyers's formula=1 No/l) all ice phase microphysical characteristics have their max. values, and glaciation time is ~ 3 hrs. Simulated fields of SS show that initially intensively glaciated clouds continue their development as icy clouds in sub-saturated w.r.t. water conditions. In E90 that is similar to E92 but with constant in Meyers's formula reduced by one order of magnitude, liquid phase exists during the course of model integration (12 hrs), and LWC is reduced by an order of magnitude in ~ 9 hrs. Crystal conc. in E90 is 8 times less than in E92, and Re in E90 have max values of ~ 350 micron as compared to 250 in E92. E93, in which only the second IIP is active, is characterized by persistent liquid phase with max. values of droplet conc. and LWC near cloud top, significantly increased crystal conc. and min. values of ice radar reflectivity and precipitation flux. Crystal Re in E93 are also minimal. Both IIP are active in E94 that combines microphysical features of E90 & E93. Its distinguished features are reduced droplets conc. and LWC as compared to E93, increased ice conc. and reduced Re as compared to E90, with about the same radar reflectivity and precipitation fluxes for both runs. E94 results also agree qualitatively with M-PACE data (McFarguhar et all 2007) that show typical vertical structure of single-layer clouds: existence of mainly liquid and ice phases at cloud top and near cloud base, respectively, with mixed phase in the middle of cloudy region. We expect that relative importance of the second IIP will increase for long-lasting Arctic stratocumulus clouds within temperature range between -10C and -20C in less SS w.r.t. ice environment than used in our runs.

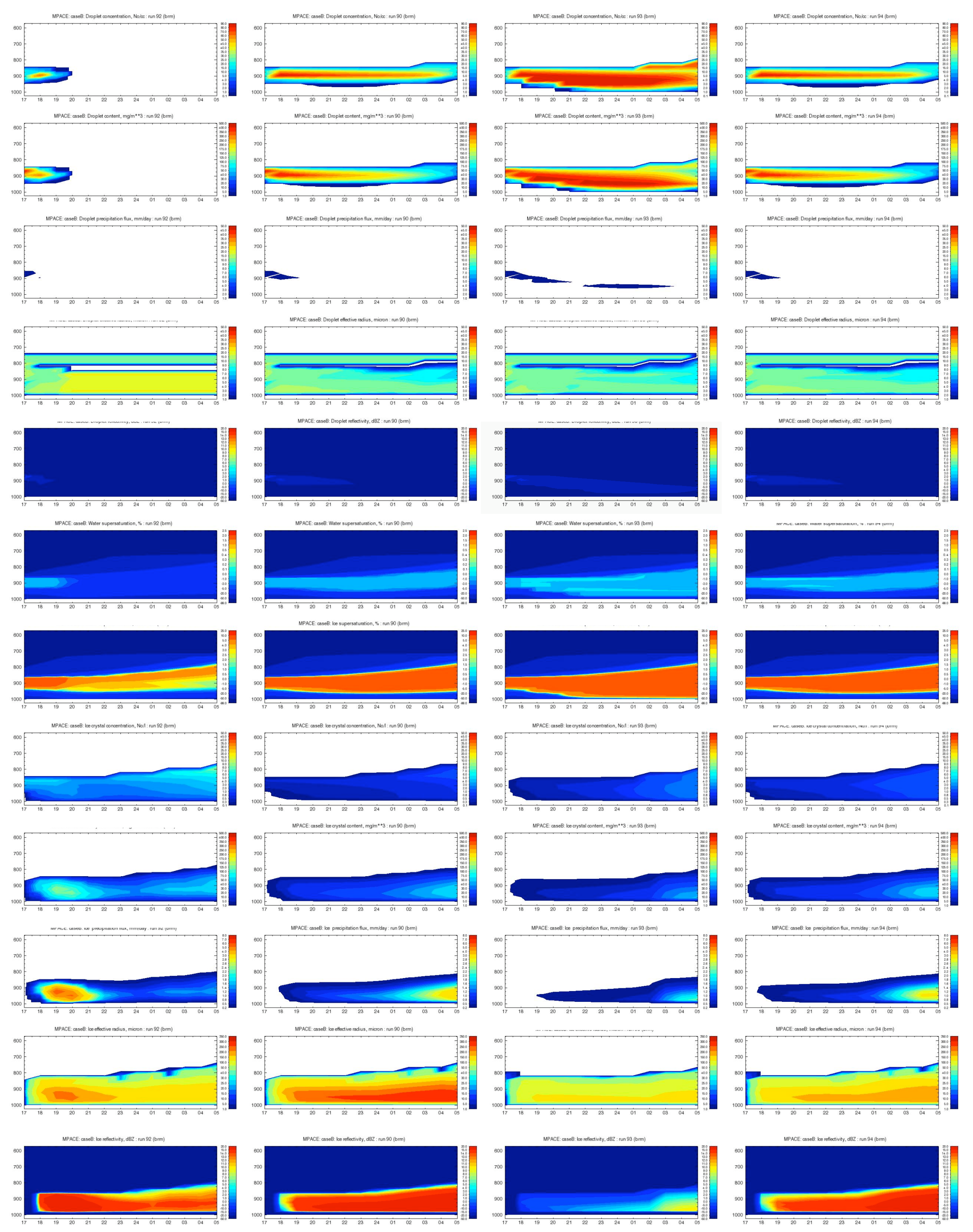

Fig. 3 Droplet concentration, content, precipitation flux, effective radius, and radar reflectivity, supersaturation w.r.t. water and ice, ice concentration, content, precipitation flux, effective radius, and radar reflectivity (top to bottom) in E92, E90, E93, & E94 (left to right).

Table 1
Max. values of conc. (C), content (M), effective radii (Re), radar reflectivity (D), and precipitation flux (R) for ice (i) and liquid (w)

		E90	E92	E93	E94	E95	E96	E97	E98
Ci	No/l	1.2	9.2	2.7	1.8	N/A	N/A	N/A	N/A
Mi	mg/m³	63.9	153.9	52.1	56.4	N/A	N/A	N/A	N/A
Rei	micron	339.5	265.8	183.6	247.8	N/A	N/A	N/A	N/A
Di	dBZ	26.8	27.6	11.1	25.7	N/A	N/A	N/A	N/A
Ri	mm/day	3.6	7.0	2.4	3.1	N/A	N/A	N/A	N/A
Cw	No/cc	102.3	72.5	148.5	101.9	144.3	21.1	140.4	21.1
Mw	mg/m³	493.5	468.1	620.1	490.7	734.1	468.1	512.4	468.1
Rew	micron	19.7	26.1	19.6	19.7	19.4	29.8	84.9	69.3
Dw	dBZ	-11.6	-11.6	-11.6	-11.6	-11.6	-11.1	5.5	-2.4
Rw	mm/day	2.2	2.2	2.2	2.2	2.2	2.2	7.0	2.9

Summary: Based on radar measurements and spiral flight data, and our simulations, including those not shown, we conclude:

1. The shape of CCN spectrum is of crucial importance for maintenance of liquid phase and cloud glaciation time.

2. Glaciation time is mainly determined by Bergeron-Findeisen process, e.g. deposition growth of ice at the expense of evaporated cloud droplets, as a consequence of implied idealized large-scale forcing.

3. For an idealized environment we can reproduce radar measurements that show the existence of mixed clouds with max. reflectivity ~ 20 dBZ.

4. In terms of ice conc. and Re, modeled values are in better agreement with spiral flight data if both ice initiation mechanisms are included.

5. Despite the microphysics scheme accounting for ice enhancement, e.g. riming-splintering, the idealized environment (especially the initial size distributions for water droplets at different altitudes) and implied large-scale forcing are not favorable for ice multiplication.

6. We cannot simulate cloud regeneration after midnight as is clearly seen in radar images.

7. More realistic representation of hydrometeors' fluxes dictates accounting for processes of aggregates and graupel formation that are switched off in our runs.

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