4.5 THE INFLUENCE OF ICE NUCLEATION MODE AND ICE VAPOR GROWTH ON SIMULATION OF ARCTIC MIXED-PHASE CLOUDS

Alexander Avramov* and J.Y. Harrington
The Pennsylvania State University, University Park, PA 16802

1. INTRODUCTION

Mixed-phase arctic stratus clouds are the predominant cloud type in the Arctic and through various feedback mechanisms exert a strong influence on the Arctic climate. Perhaps one of the most intriguing of their features is that they tend to have liquid tops that precipitate ice. Despite the fact that this situation is colloidally unstable, these cloud systems are quite long lived - from a few days to over a couple of weeks. It has been hypothesized that mixed-phase clouds are maintained through a balance between liquid water condensation resulting from the cloud-top radiative cooling and ice removal by precipitation (Pinto, 1998; Harrington et al., 1999). In their modeling studies Harrington et al. (1999) and Harrington and Olsson (2001) found that the maintenance of this balance depends strongly on the ambient concentration of ice nuclei (IN). In a follow-up study, Jiang et al. (2000), using only 30% of IN concentration predicted by Meyers et al. (1992) IN parameterization were able to obtain results similar to Harrington et al. (1999) and the observations reported by Pinto (1998). The IN concentration measurements collected during the Mixed-Phase Arctic Cloud Experiment (M-PACE), conducted in October 2004 over the North Slope of Alaska and the Beaufort Sea (Verlinde et al., 2006), also showed much lower values (Prenni et al., 2006) than those predicted by currently accepted IN parameterizations (e.g. Meyers et al., 1992). In addition, the IN concentrations measured during M-PACE are more than an order of magnitude lower than springtime measurements in the Arctic reported by Rogers et al. (2001) using the same instrument (Prenni et al., 2006). This indicates that a seasonal dependence of IN concentration exists.

IN can nucleate ice crystals in four different modes: condensation-freezing, deposition, contact and immersion freezing. Morrison et al. (2005) examined the sensitivity of arctic mixed-phase clouds to the ice nucleation mode using a 1-D model with a dual moment bulk microphysics scheme. They showed that the liquid phase amount is highly sensitive to the number concentration of deposition/condensation-freezing nuclei and much less sensitive to the number of contact nuclei. They also developed a conceptual model of arctic mixed-phase clouds that explains their persistence through the rapid depletion of deposition/condensation-freezing nuclei and self-regulating negative feedback involving drop freezing by contact nucleation. In this scenario, contact nucleation controls the continual production of ice in mixed-phase arctic clouds (Morrison and Pinto, 2005). While these results support the general conclusions of earlier work (e.g. Harrington et al., 1999 and Harrington and Olsson, 2001) there is a discrepancy with respect to the role of contact nucleation. Those earlier works suggest that contact nucleation plays a limited role in ice nucleation within arctic mixed-phase clouds (at least within the RAMS model, which was used in those studies.) In this paper we further investigate the influence of ice nucleation mode on arctic mixed-phase clouds utilizing the extensive set of observations collected during M-PACE. We examine the roles of both deposition/condensation freezing and contact nucleation in our simulations.

2. MODEL CONFIGURATION

The model used in this study is the Colorado State University version of Regional Atmospheric Modeling System (RAMS@CSU) (Cotton et al., 2003) with two-moment microphysics (Walko et al., 1995; Meyers at al., 1997) and two-stream radiation scheme (Harrington and Olsson, 2001). It also incorporates the Los Alamos National Laboratory sea-ice model (Hunke and Lipscomb, 1999).

The microphysical package has seven hydrometeor categories: cloud droplets, rain, pristine ice, snow, aggregates, graupel and hail. Three of the four heterogeneous nucleation modes are present in the model – deposition, condensation-freezing and contact nucleation. Deposition and condensation-freezing nucleation are parameterized as a function of ice supersaturation following Meyers et al. (1992). Contact nucleation rates due to thermophoresis,

**Corresponding author address:* A. Avramov, Dept. of Meteorology, Penn State University, University Park, PA 16802
e-mail: lz4ax@psu.edu

diffusiophoresis and Brownian motion are given in Cotton et al. (1986) and the number of IN available for contact freezing as a function of temperature is described in Meyers et al. (1992). During a simulation, the model keeps track of the number of IN for both contact and condensation-freezing nucleation mode. The importance of IN depletion has been emphasized in a number of studies – Harrington and Olsson (2001), Morrison et al. (2005), Prenni et al.(2006).

The model is configured with three nested grids (fig. 1):

- grid #1 has 64 km resolution and covers the entire state of Alaska – 3392x2368 km;
- grid #2 has a resolution of 16 km and is centered on the North Slope of Alaska, covering a 1296x976 km area;
- grid #3 has 4 km grid spacing, it is centered on the north shore (M-PACE domain) and covers area of 312x212 km.

Vertical grid spacing on all three grids starts with 50 m spacing at the surface and stretches to 1000 at the higher levels.

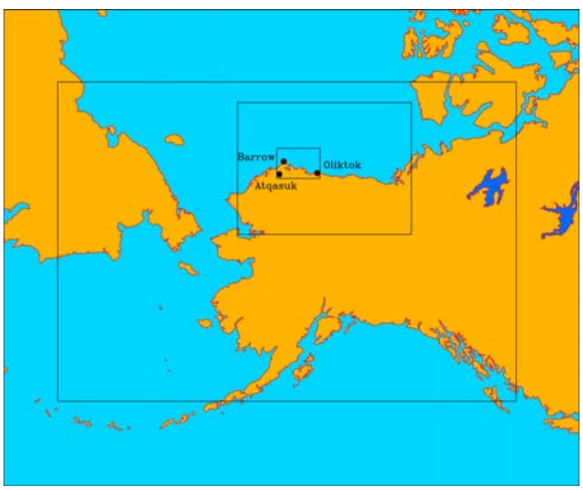


Figure 1. Map of computational domain

ETA model analysis fields, DMSP SSM/I daily ice dataset and NCEP OI SST weekly data were used to initialize the model. In addition, the outer RAMS grid was nudged to the ETA 12-hourly forecasts.

3. CASE DESCRIPTION

We simulated the time period of October 9-11, 2004, during which the North Slope of Alaska and the adjacent ocean were covered by extensive mixed-phase clouds. Synoptic situation during the simulation period was determined mainly by the high pressure center developing over sea-ice pack to the north east of the Alaska coast. This high, coupled with the surface low over the Aleutians, intensified the pressure gradient over the area and created favorable conditions for strong easterly winds moving cold air off the pack ice over the relatively warm ocean surface. This synoptic situation persisted throughout the simulation period (Fig. 2). Over the course of the next several days a series of wave-like disturbances originated near the pack ice and propagated southwest

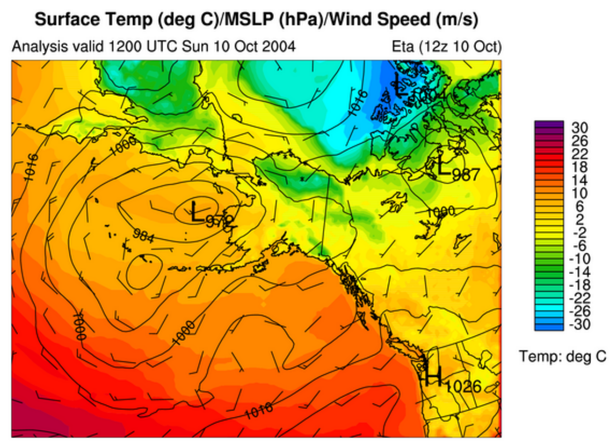


Figure 2. ETA surface analysis for 12 UTC October 10, 2004

through the area. The MODIS visible image shown on Fig. 3 and the University of Wisconsin High Spectral Resolution Radar (HRSL) image (Fig. 4) illustrate the structure of the observed cloudiness.

Figure 3. MODIS visible image of the North slope of Alaska on October 10, 2004

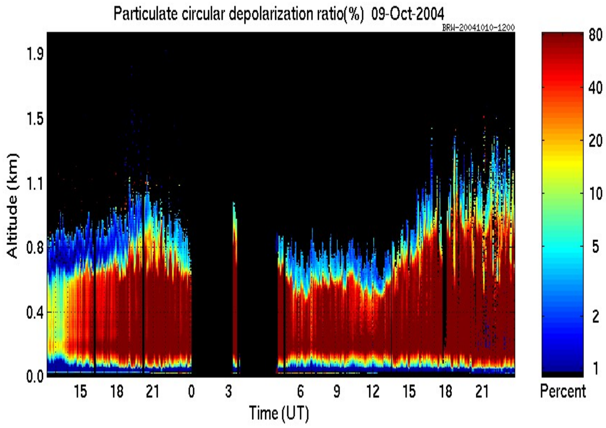


Figure 4. Lidar depolarization ratio (<2 liquid, >2 ice) over Barrow, AK

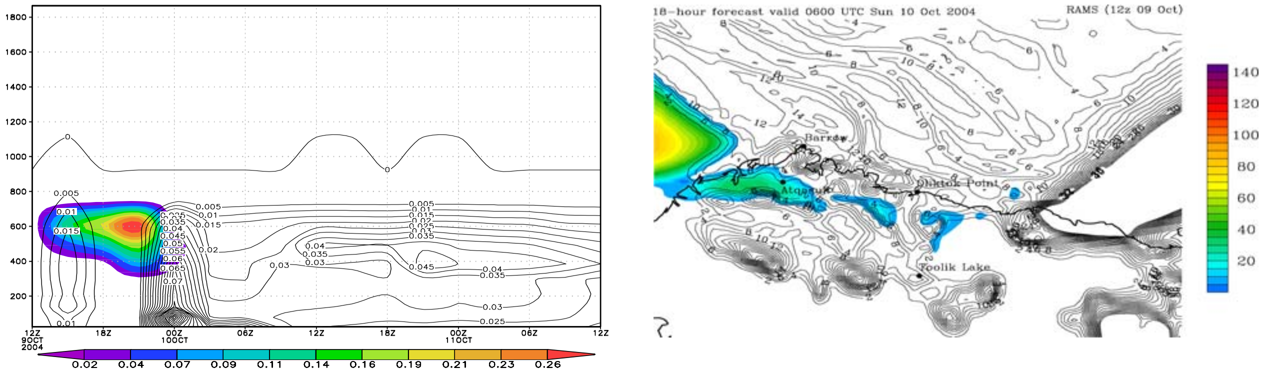
4. RESULTS

A number of sensitivity tests were performed to examine the impact of IN concentrations and nucleation mode on the life-time of the simulated mixed-phase cloud. Our base simulation uses Meyers et al. (1992) parameterizations for both deposition-condensation-freezing IN and IN available for contact nucleation. Results from the "base" (Standard IN Dep) run are shown on Figure 5. After the initial spin-up, these relatively high IN concentrations lead to a rapid conversion of the liquid phase to ice, most of which then precipitates. 18 hours after the beginning of the simulation, in contrast with observations, the cloud water throughout the domain of grid #2 is almost completely depleted and the region is covered by thin ice clouds (Fig. 5b). The same simulation was then repeated using a new deposition/condensation-freezing IN parameterization, derived from the "in-situ" IN measurements taken during M-PACE. This new parameterization has a similar functional form as Meyers et al., (1992) but the predicted IN concentrations are approximately 26 times lower. Since we did not have contact nucleation measurements data, we assumed that the IN available for contact nucleation must be reduced by the same factor as deposition/condensation-freezing IN. When these, much lower and eventually more realistic for the autumn Arctic environment values of IN concentration were used in the new simulation, the cloud structure drastically changed. A persistent stratus cloud layer with smaller amounts of ice is produced. As it is illustrated on Figure 6, the liquid and ice coexist throughout the entire simulation in better agreement with observations. Another two simulations where deposition/condensation-freezing IN were increased by a factor of two (2xMPACE IN Dep) and ten (10xMPACE IN Dep) were performed to check how sensitive the simulated cloud fields are. While both simulations are still able to maintain a mixed-phase cloud deck, the liquid phase gradually decreases as the IN concentrations increase. In all simulations, both deposition/condensation-freezing and contact IN are depleted due to ice crystal nucleation and precipitation. On Figure 7 the modeled LWP and net infrared radiative flux for all simulations are compared against the observations made at Oliktok point. When the depletion of IN is turned off (MPACE IN, No Dep), even the MPACE-derived IN concentrations lead to a rapid glaciation, which is consistent with the previous studis of Harrington and Olsson (2001) and Morrison et al. (2005). The "MPACE IN Dep" agrees quite well with the observations, although the modeled LWP is smaller. However, it still represents a significant improvement over the standard IN case (Standard IN Dep). Also, it is important to note the big difference in the modeled net infrared fluxes between these two simulations, which can have a substantial impact on the regional climate.

Finally, to check the sensitivity of the simulated clouds to the contact IN parameterization, simulations with concentrations of available for contact nucleation IN from 26 times lower to 26 times higher than those predicted by Meyers et al. (1992) were conducted. Despite the wide range of IN concentrations no significant sensitivity to contact IN was found. Even for the almost unrealistic case of available contact IN concentration 26 times higher than Meyers et al. (1992), contact nucleation rates and formed crystal concentrations are not significantly larger than those for deposition/condensation-freezing – Figure 8.

5. CONCLUSIONS

In this study we have investigated the influence of IN concentrations and ice nucleation modes on the structure and life-time of simulated arctic mixed-phase clouds. Using IN parameterization derived from "in-situ" IN measurements results in a realistic mixed-phase cloud layer, very similar to the observed one. In contrast, when IN concentrations typical for mid-latitudes are used, the cloud layer rapidly glaciates. Our results show that the structure and the lifetime of simulated arctic mixed-phase clouds



a) b)

Figure 5. Time evolution of the liquid (shaded) and ice (contoured) water mixing ratio [g/kg] over Barrow (a), and liquid (shaded) and ice water path (contoured) [g.m^{-2}] at 18 hours of simulation time (b) – “base run”

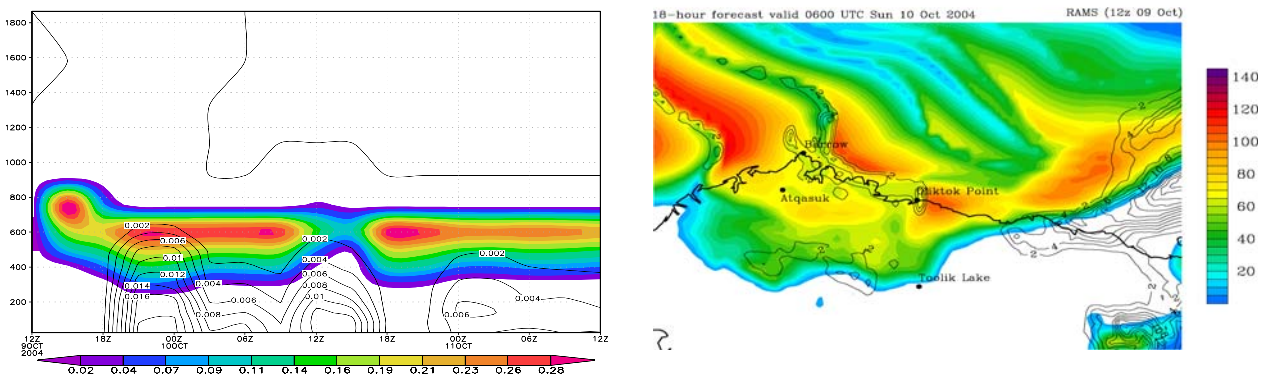


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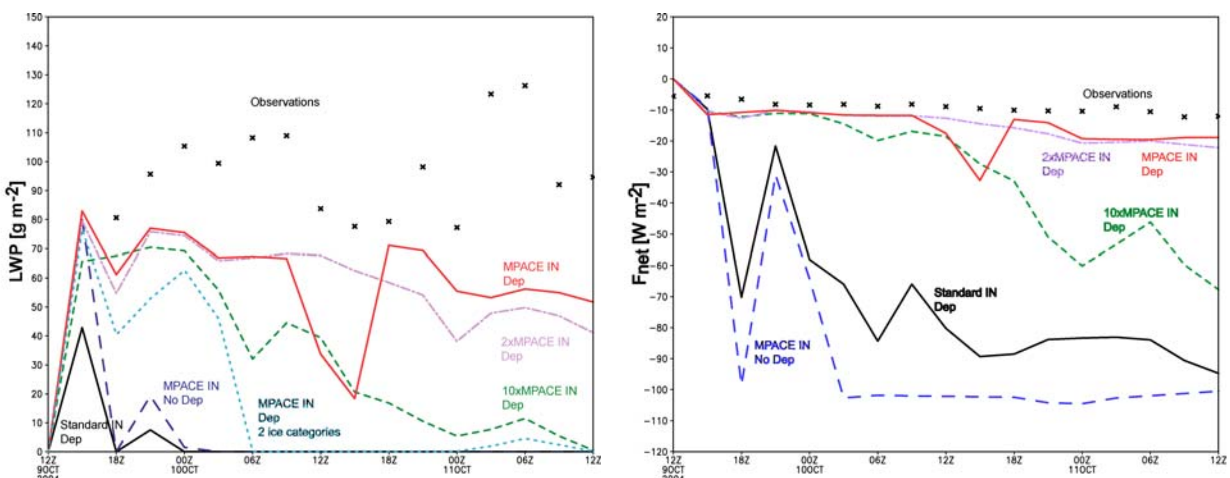
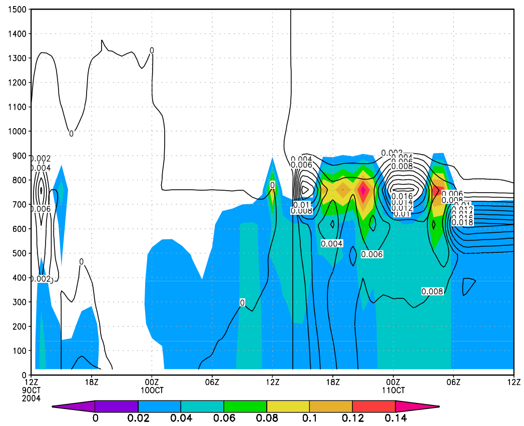
Figure 6. Time evolution of the liquid (shaded) and ice (contoured) water mixing ratio [g/kg] over Barrow (a), and liquid (shaded) and ice water path (contoured) [g.m^{-2}] at 18 hours of simulation time (b) – “MPACE IN Dep”

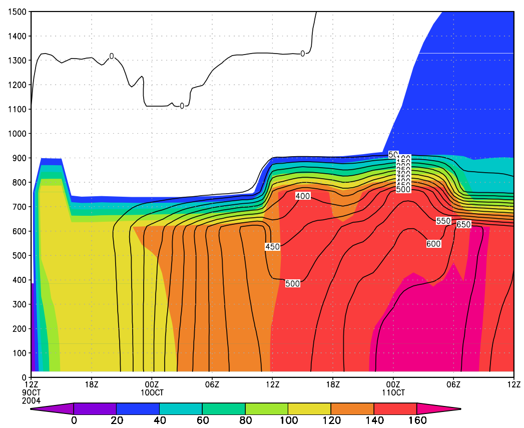


a) b)

Figure 7. Liquid water path [g.m^{-2}] (a) and net longwave radiative flux [W.m^{-2}] (b) at Oliktok point for different sensitivity runs: base run (black), M-PACE derived IN parameterization (red), two times increased IN concentration (magenta), 10 times increased IN concentration (green), two ice categories (light blue), diagnosed IN (dark blue)



a)



b)

Figure 8. Deposition/condensation-freezing (shaded) and contact nucleation (contoured) rates [$m^{-3}s^{-1}$] (a), and the number of IN per m^3 depleted through deposition/condensation-freezing (shaded) and contact nucleation (contoured) (b)

is highly sensitive to deposition/condensation-freezing IN and shows almost no sensitivity to the number of IN available for contact nucleation. As a consequence of that, we find the deposition/condensation-freezing nucleation to be the dominant, controlling heterogeneous nucleation mode in our simulations. While the lower sensitivity to contact IN is consistent with results of previous studies (e.g. Harrington et al., 1999 and Harrington and Olsson, 2001, Morrison et al., 2005) our conclusion about the dominant role of deposition/condensation-freezing nucleation contradicts Morrison et al., (2005) findings and requires further investigation. Finally, results from our sensitivity tests suggest that in order to correctly simulate arctic mixed-phase stratus clouds, models must correctly predict not only the number of heterogeneously nucleated ice crystals but also the cloud processing and removal of IN through precipitation.

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