P1.12 AN LES STUDY OF ICE MICROPHYSICAL INFLUENCES ON ROLL CLOUD STRUCTURE AND DYNAMICS DURING OFF-ICE FLOW

Jerry Y. Harrington*
Department of Meteorology, Pennsylvania State University, University Park, Pennsylvania

Peter Q. Olsson
Alaska Experimental Forecast Facility, University of Alaska Anchorage, Anchorage, Alaska

1. INTRODUCTION

Clouds streets, and associated roll convection, are fairly common features of the atmospheric boundary layer (BL). While these organized cumuliform clouds are found over many regions of the planet, they are quite ubiquitous near the edge of the polar ice sheets. In particular, during periods of off-ice flow, when cold polar air flows from the ice pack over the relatively warm ocean waters, strong BL convection develops along with frequent rolls. A recent wintertime climatology of cloudiness over the marginal ice zone (MIZ) Brummer and Pohlman (2000) showed most of the total cloud cover is due to cloud streets.

A significant number of observational studies of BL roll clouds have been undertaken (e.g. Hein and Brown, 1988). However, most modeling studies of the BL formed during off-ice flow have either been run dry or include only liquid-phase microphysics (e.g. Chlond, 1992). In an effort to examine the influences of mixed-phase microphysics on the BL evolution during off-ice flow, Olsson and Harrington (2000) used a 2-D mesoscale model coupled to a bulk microphysical scheme (see section 2). Their results showed that mixed-phase clouds produced more shallow BLs with weaker turbulence than liquid-phase cases. Furthermore, their results showed that because of the reduced turbulent drag on the atmosphere in the mixed-phase case, regions of mesoscale divergence in the MIZ were significantly affected. A follow-up 2-D study (Harrington and Olsson, 2001) showed that the reduced turbulent intensity in mixed-phase cases was due to precipitation. Ice precipitation caused downdraft stabilization which fed back and caused a reduction in the surface heat fluxes.

Fully 3-D LES studies of roll convection have begun to separate important causal relationships (see Glendening, 2000). Chlond's (1992) liquid cloud studies showed that condensation is vital to the maintenance of turbulent intensity and cloud structure. Furthermore, their simulations suggest that radiative cooling, subsidence, and variation in surface temperature all importantly affected turbulent intensity. Rao and Agee (1996) used an LES to simulate mixed-phase cloudy convection. Their comparison of liquid and mixed-phase cloudy BL convection showed that turbulent intensity is weaker and skewness is greater in the mixed-phase case. Furthermore, this work showed that the mixed-phase case produced 2-D roll-like convection whereas the liquid case produced spoke-like convection.

In this work, we begin to extend the work of Olsson and Harrington (2000) and Harrington and Olsson (2001) by examining the impacts of ice microphysics on roll convection.

2. NUMERICAL MODEL AND CASE

The numerical model used is the LES version of the Regional Atmospheric Modeling System (RAMS) with the bulk microphysics of Walko et al. (1995). This model represents the evolution of liquid and ice hydrometeor species. The microphysics is coupled to the radiation scheme of Harrington and Olsson (2000) which includes scattering and absorption by liquid and ice.

The case used for our simulations was observed during the Radiation and Eddy Flux Experiment (REFLEX II) in 1993 off the coast of Spitsbergen. The off-ice flow on this day brought cold air (T_{surace} ~ -35C) over a relatively warm ocean (SST ~ 0C) producing intense convection and rapid BL development (Lupkes and Schultzen 1996). This case produced organized roll convection (see Kottmeier et al. 1994) a short distance off the ice edge (~ 50 km) which was transformed to cellular convection further over the open ocean (~ 200 km).

3. NUMERICAL STUDIES

The RAMS model was set up with a (x,y) domain size of 8 by 17 km. The grid-spacing used was (ΔX,ΔY) = 120 m and ΔZ = 40 m. To emulate the effects of off-ice flow, the lower SST boundary of the model was warmed using the SST-gradient given in Lupkes and Schultzen (1996). Because of the intense computational costs, only two cases were simulated. The first case used only liquid phase microphysics with no sedimentation (*case LP*) while the second case used mixed-phase microphysics with sedimentation (*case MP*). Simulations were carried out for a total of 8 hours, which corresponds to a distance of 240 km from the ice edge.

**Corresponding author address:* J. Harrington, Dept. of Meteorology, Penn State University, University Park, PA, 16802.
email: harring@mail.meteo.psu.edu

3.1 Snapshots of Model Fields

Figure 1 shows snapshots of the total water path (WP) and average vertical motion (w) for case LP and MP after 1 hour of simulation time. At this time, roll convection has

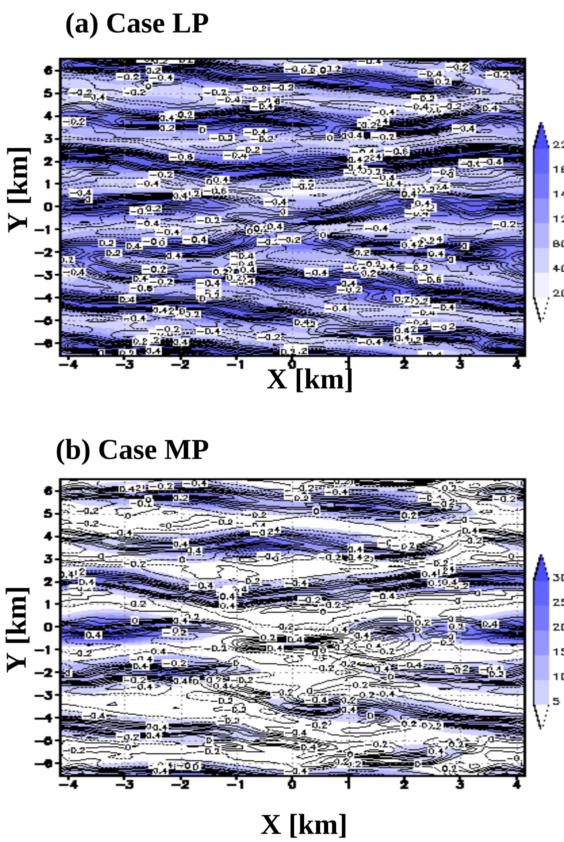

Figure 1. Total water path (g m^{-2}, shaded) and average vertical motion (m s^{-1}, contoured).

developed along with distinct cloud streets. The BL is 1 km deep and the average vertical motions are of approximately equal magnitude for both cases. Perhaps the most obvious difference between the two simulations is that updrafts are cloudy whereas downdrafts are dry in the MP simulation. The case with liquid-only clouds (LP) produces essentially 100% cloud fraction and the rolls are recognizable as locally high regions of WP collocated with updrafts. This basic difference, dry downdrafts in the mixed-phase case and moist downdrafts in the liquid case, is characteristic of the entire simulation. As Olsson and Harrington (2000) and Harrington and Olsson (2001) have shown, the dry downdrafts in the mixed-phase case are due to ice precipitation which falls predominately, and continually, from updrafts.

3.2 Analysis of Case Evolution

Temporal evolution of the WP for both cases is shown in Figure 2. Similar to Olsson and Harrington's (2000) simulations, the WP in case LP develops rapidly and continues to increase throughout the simulation. Clouds develop initially in case MP, however this water is quickly precipitated to the surface. After ~ 100 min of simulation time cloudiness increases

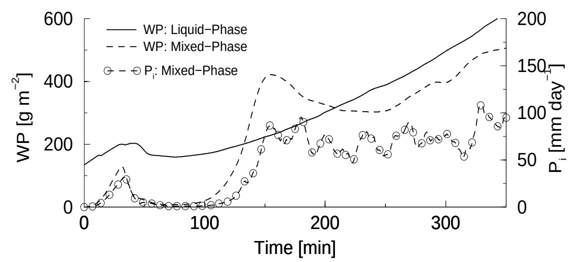

Figure 2. Time-series of total water path (WP) for MP and LP and instantaneous precipitation rate (P_i) for MP.

rapidly in MP. (This delay in the onset of persistent cloud cover is due to the fact that ice precipitation significantly warmed the BL in the first 30 min.) As might be expected, P_i increases concurrently with WP in the mixed-phase case. Note that after about 150 min of simulation time, the WP in case MP is fairly steady as are the precipitation rates. This result stands in stark contrast to some of our 2-D results (Olsson and Harrington, 2000) which showed that precipitation causes large oscillations in the WP field. However, Harrington and Olsson (2001) showed that the above steady-WP situation is strongly dependent in ice nuclei concentrations and feedbacks with surface heat fluxes.

The dynamics of the roll convection are strongly modulated by ice precipitation as is shown in Fig. 3. The vertical

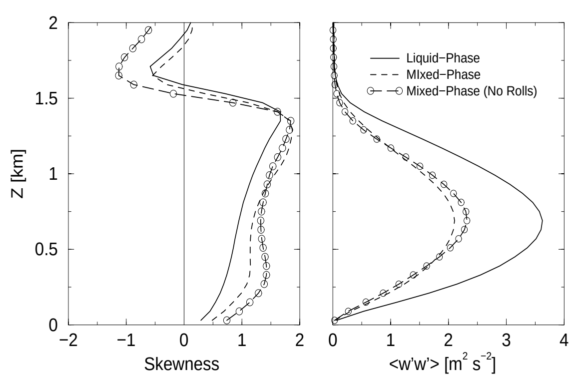

Figure 3. Profiles of the vertical component of TKE and vertical velocity skewness after 4 hours.

component of TKE (w'w'), averaged over the 4^{th} simulation hour, is shown for both the LP and MP cases. Note that w'w' is significantly greater at every height in case LP. This result is consistent with other time periods in the simulation as Fig. 4 shows. Throughout the simulation, the vertical component of turbulent kinetic energy (TKE) is significantly less for case MP indicating weaker BL circulations. In fact, the convective velocity scale for LP is roughly 7 m s^{-1} whereas it is 4 m s^{-1} in case MP Using 2-D simulations Harrington and Olsson (2001)

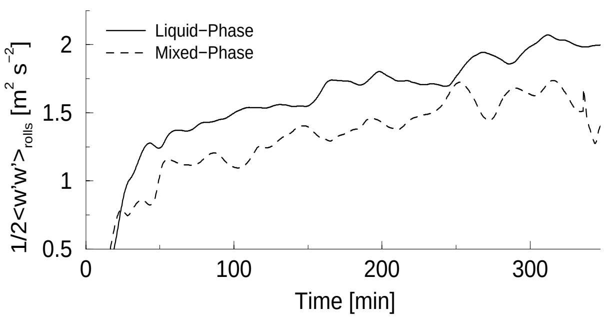

Figure 4. Time-series of the vertical component of TKE derived for rolls and averaged over BL depth.

show that this reduction in vertical TKE is due to two coupled processes. First, the buoyancy of downdrafts is reduced by precipitation warming in the mixed-phase case. Second, the sensibly warmed BL and reduced surface winds (through reduced momentum fluxes) produce weaker sensible heat fluxes out of the surface in case MP. That this is also the case for our 3-D roll clouds is shown in Figs. 5 and 6.

Figure 5 shows the buoyancy flux, partitioned between updrafts and downdrafts, for LP and MP. The buoyancy flux is reduced overall in case MP. Note that buoyancy production of

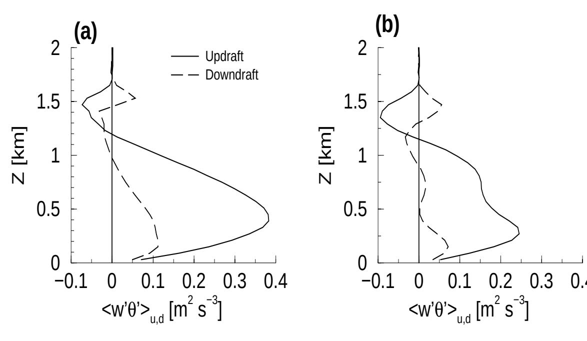

Figure 5. Profiles of the buoyancy flux in updrafts and downdrafts for (a) LP and (b) MP.

vertical TKE is positive in both updrafts and downdrafts in the liquid case (with negative values near cloud top which are due to entrainment). However, in case MP, the buoyancy flux is significantly reduced. Updrafts experience a reduction in buoyancy through excessive precipitation loading and through a reduction in surface heat fluxes (see below). As Harrington and Olsson (2001) have shown, ice precipitation sensibly warms and dries updrafts which is eventually realized as a buoyancy consumption within downdrafts. In the fully 3-D case presented here, this buoyancy consumption mechanism is not as prevalent within downdrafts; instead buoyancy fluxes are nearly zero throughout most of the simulation.

The consumption of TKE generated by ice precipitation has a significant impact on the surface heat fluxes. As Fig.6

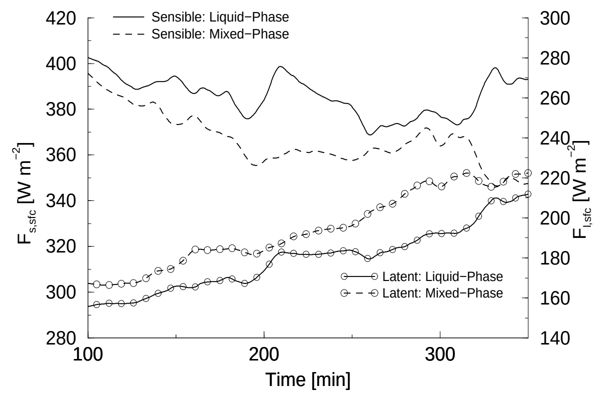

Figure 6. Time-series of sensible and latent heat flux.

shows, sensible heat fluxes are reduced by 10 - 40 W m^{-2} whereas latent heat fluxes are increased by 5 - 20 W m^{-2} in case MP. The sensible heat fluxes at the surface are reduced because the BL in the mixed-phase case is warmed through ice precipitation. This makes the temperature difference between the atmosphere and ocean surface smaller. Latent heat fluxes, however, have increased in the mixed-phase case because the atmosphere is dried and warmed (relative to the liquid case) through ice precipitation.

Thus, there appears to be a positive feedback between direct ice precipitation reduction of TKE and indirect reductions in TKE through smaller surface heat fluxes. These results are in general agreement with the 2-D simulations of Harrington and Olsson (2001).

3.3 Eddy Structure and Roll Wavelength

The impact of precipitation on the dynamics of the roll circulations described above also has a significant influence on eddy structure and roll cloud spacing. The skewness shown in Fig. 3 for the MP and LP cases illustrates this point. Skewness is a measure of the strength and width of updraft and downdraft entities. Positive (negative) values of skewness indicate narrow, strong updrafts (downdrafts) with broad, weaker downdrafts (updrafts). Note that the skewness throughout most of the BL is positive which is typically the case for surface driven convection. The negative values of skewness near the top of the BL are typically considered to be related to cloud top radiative cooling which assists in the formation of downdrafts. The skewness in the mixed-phase case is larger than the liquid phase case and appears to have a minimum near the middle of the BL. This structure is consistent with the LES studies of Rao and Agee (1996).

Since the updrafts in the mixed-phase case are actually slightly weaker than the liquid phase case, the larger skewness must be due to the fact that downdrafts in the MP case are broader. In fact, that is the case. Since downdrafts in the MP case are stably stratified by ice precipitation, larger mass convergence is required in order to mechanically initiate downdrafts and this leads to broader sinking regions. As might be

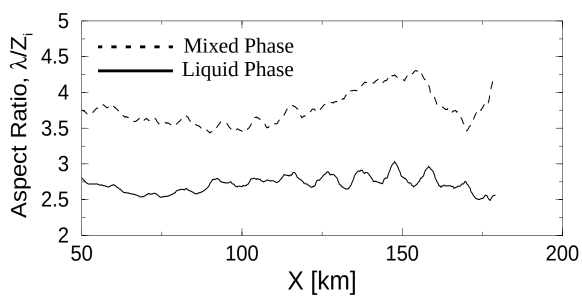

Figure 7. Roll aspect ratio vs. distance from ice edge.

expected, this process affects the aspect ratio of the rolls (Fig. 7). Aspect ratios (roll wavelength to BL depth) is fairly constant and between 2.5 and 3 for the liquid case whereas it is around 4 for the mixed-phase case. This is simply due to the fact that downdraft regions are relatively broad in the mixed phase case.

Finally, comparisons with observations of thermal structure and roll cloud aspect ratio show that the mixed-phase case produces fields that are much more closely aligned with reality.

4. CONCLUDING REMARKS

In this study, we used the LES mode of the RAMS model with explicit microphysics to examine the influence of ice phase processes on roll cloud development and dynamics. This study was conducted, in part, because Harrington and Olsson (2001) found that ice-phase processes strongly affected the evolution of the cloudy BL over the marginal ice zone. However those results were 2-D and, hence, did not capture the roll dynamics prevalent in the observed case.

Our studies show that the processes discussed in Harrington and Olsson (2001) appear to occur, in a weaker sense, in the fully 3-D simulations. Ice precipitation from mixed-phase clouds produces dry downdraft regions and true cloud streets. The TKE is reduced in the mixed-phase case through ice precipitation which stabilizes downdrafts and reduces surface sensible heat fluxes. This produces broader downdrafts in the mixed-phase case with greater skewness and roll aspect ratios than the liquid cloud simulation.

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