A Modeling Case Study of Mixed-Phase Clouds over the Southern Ocean and Tasmania

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ABSTRACT

The cloud structure associated with two frontal passages over the Southern Ocean and Tasmania is investigated. The first event, during August 2006, is characterized by large quantities of supercooled liquid water and little ice. The second case, during October 2007, is more mixed phase. The Weather Research and Forecasting model (WRFV2.2.1) is evaluated using remote sensed and in situ observations within the post frontal air mass. The Thompson microphysics module is used to describe in-cloud processes, where ice is initiated using the Cooper parameterization at temperatures lower than \(-8^\circ C\) or at ice supersaturations greater than 8%. The evaluated cases are then used to numerically investigate the prevalence of supercooled and mixed-phase clouds over Tasmania and the ocean to the west. The simulations produce marine stratocumulus-like clouds with maximum heights of between 3 and 5 km. These are capped by weak temperature and strong moisture inversions. When the inversion is at temperatures warmer than \(-10^\circ C\), WRF produces widespread supercooled cloud fields with little glaciation. This is consistent with the limited in situ observations. When the inversion is at higher altitudes, allowing cooler cloud tops, glaciated (and to a lesser extent mixed phase) clouds are more common. The simulations are further explored to evaluate any orographic signature within the cloud structure over Tasmania. No consistent signature is found between the two cases.

1. Introduction

The Southern Ocean and its accompanying air mass are among the most pristine environments on earth. A recent satellite climatology employing Cloudsat (Mace et al. 2007) concludes that the majority of clouds over this region can broadly be categorized into two types. The most common are low and shallow having bases and tops below 3 km. The less prevalent type is relatively deeper clouds having bases below 3 km and tops between 5 and 10 km. Furthermore, typically between 70%–100% of the Southern Ocean region is covered in hydrometeors. These findings are consistent with Bennartz (2007) who found that up to 89% of clouds over this region were likely to be precipitating. Microphysical conditions are found to be homogeneous showing little variability over the entire region.

In addition to satellite climatologies, in situ microphysical observations have been documented by many authors. The Southern Ocean Cloud Experiments used aircraft measurements to investigate the organization of convection and evolution of the droplet size distribution in stratocumulus clouds (Boers et al. 1997). Jensen et al. (2000) investigated the dynamics of marine boundary layer clouds and Yum and Hudson (2004) studied the differences between summer and winter cloud condensation nuclei (CCN) and other microphysical characteristics. The Aerosol Characterisation Experiments (ACE-1) encountered a variety of cloud types from frontal cloud bands to shallow cumulus in the region 40°–55°S, investigating diverse aspects of the marine boundary layer from cloud droplet concentrations (Boers and Krummel 1998) to turbulent mixing (Russell et al. 1998). Long-term ground-based CCN climatologies exist from the northwest coast of Tasmania (Gras 1995), and show that
concentrations are usually between 10 and 110 cm$^{-3}$ with an average of around 70 cm$^{-3}$, consistent with Bennartz (2007).

In situ observations of mixed-phase clouds with particular interest in supercooled liquid water (SLW) have been documented by two cloud seeding experiments over the island of Tasmania, 1964–71 (Smith et al. 1979) and 1979–83 (Ryan and King 1997). Interestingly, both experiments reported increases in precipitation associated with cloud seeding periods. Furthermore, a recent 46-yr study (1960–2005) by Morrison et al. (2009) finds consistent increases in precipitation. Quantitative records of SLW were obtained by aircraft during the 1979–83 experiment. It was found that extended regions (5-min averages) of SLW with values $\approx 0.3$ g m$^{-3}$ between $-6^\circ$ and $-8^\circ$C were common. This is a large amount of SLW relative to similar studies in other parts of the world, for example, eastern Canada where SLW contents of $\approx 0.1$ g m$^{-3}$ were common within a similar temperature range (Guan et al. 2001, 2002; Vaillancourt et al. 2003), or the Sierra Nevada where the most common peak SLW content (per flight track) was $\approx 0.1$ g m$^{-3}$ (Deshler and Reynolds 1990). Given that both Tasmanian cloud-seeding experiments observed mixed-phase conditions, the obvious question is the following: in which situations and environments do these conditions occur, and by what processes are they formed and maintained?

These questions are of particular importance to the climate community, the Intergovernmental Panel on Climate Change (IPCC) Working Group I reports that clouds in general represent the greatest uncertainty in climate model forecasts (Solomon et al. 2007). This has in part motivated the many earth-observing satellites such as Cloudsat (Stephens et al. 2002), which has limited ability identifying cloud phases within the cloud interior (Austin 2008).

Over the last decade the microphysical parameterizations within mesoscale numerical weather prediction models have become able to predict the mixing ratios and occasionally number concentrations of a number of hydrometeor species (Lin et al. 1983; Ferrier 1994; Walko et al. 1995; Meyers et al. 1997; Reisner et al. 1998; Tremblay et al. 2001; Thompson et al. 2004; Morrison and Pinto 2005; Thompson et al. 2008). Numerous examples regarding the modeling mixed-phase clouds in the Northern Hemisphere exist (e.g., over the North American continent), most notably Reisner et al. (1998) attempted to forecast supercooled water in the Colorado Rocky Mountains and Guan et al. (2001, 2002) and Vaillancourt et al. (2003) freezing drizzle and aircraft icing events over southeastern Canada. Farther north within the Arctic, Jiang et al. (2000) and Morrison and Pinto (2005) have modeled mixed-phase Arctic stratus. The analysis presented herein uses the Thompson bulk microphysics package (TMP; Thompson et al. 2008) to model mixed-phase clouds over the Southern Ocean and Tasmania. The scheme, originally based on Reisner et al. (1998) uses a single moment for four hydrometeor species (cloud water, rain, snow, and graupel) and a double moment for ice; originally developed for the forecasting of SLW regarding the prediction of airframe icing events. Unlike many other microphysics routines, the TMP was tested in both shallow and deep cold cloud conditions ensuring that the scheme is able to produce both supercooled and glaciated conditions. As the majority of clouds over the Southern Ocean are relatively low and shallow (Mace et al. 2007), the region may be an ideal place to test the TMP in a pristine environment.

The objectives of this paper are first, to present observations from two cloud-seeding flights made over the western region of Tasmania and second, to evaluate the Weather Research and Forecasting (WRF) NWP model employing the TMP using these in situ observations together with selected satellite and radar observations. The final objective is to investigate the situations under which mixed-phase conditions occur in the model. The present study is a detailed investigation of two case studies: the 8 August 2006 characterized by large amounts of SLW, little ice, and a relatively small amount of precipitation; and a more mixed phase event on 4 October 2007 with lower concentrations of SLW, greater concentrations of ice, and relatively larger amounts of precipitation. The following sections are organized as follows. First, the meteorology of the individual case studies is presented. Next, the WRF model configuration is defined. This is followed by an evaluation that focuses on thermodynamic profiles, cloud-top structure, radar, and in situ aircraft observations. Finally, the evolution of mixed-phase clouds over this region of the world is numerically investigated within the context of the evaluated cases.

2. Case study meteorology

Located at the northern boundary of the Southern Ocean storm tracks, the year-round meteorology of Tasmania is dominated by the passage of fronts (Simmonds and Keay 2000; Ryan et al. 1985). Both case studies evaluated herein are of wintertime frontal passages over Tasmania.

The MSLP analysis for 0000 UTC 9 August 2006 (hereafter 2006) shows a high pressure cell over the border between Western and South Australia (Fig. 1). To the southeast of this feature is a cold front associated
with a midlatitude cyclone south of Tasmania. The frontal cloud band is readily observable in an IR satellite image (Fig. 2). To the west of the front is a cloud-free band and behind this is a line of convection associated with a trough. In situ aircraft observations indicated these clouds had tops >3 km and bases <1.5 km. These cells were the target of the cloud-seeding research aircraft. Maximum SLW mixing ratio (5-min average) between −8°C and −18°C was ~0.3 g kg⁻¹. The flight track is shown in Fig. 3a.
The MSLP analysis chart (Fig. 1) for the 0000 UTC 4 October 2007 (hereafter 2007) shows a high pressure cell situated over the border of Victoria, New South Wales, and South Australia. The cold front occupies a small latitude band being confined between the high pressure cell to the north and two distinct low pressure centers situated to the southwest of Tasmania at approximately 50°S. The frontal cloud band occupies a much smaller zonal width as the prefrontal air mass is much colder, relative to the 2006 case (Fig. 2). Typical of this region marine boundary layer clouds are observed in the pre- and postfrontal air mass. The aircraft sampled clouds within the trailing edge of the frontal cloud band. Cloud tops were 2.5–3.5 km with bases <1.5 km. The conditions regarding seeding suitability during this event were less favorable because of a greater fraction of mixed-phase clouds being present. Maximum SLW was $\sim0.1$ g kg$^{-1}$ (5 min) at approx. $-10^\circ$C; a second seeding track was sought farther south to find more appropriate conditions; these did not occur (Fig. 3b).

### 3. Model configuration

The Advanced Research WRF (ARW) version 2.2.1 is a nonhydrostatic Eulerian solver developed by multiple government agencies in the United States (Skamarock et al. 2007). The model was configured with 64$\eta$ levels with a vertical resolution of 40 m at the surface extending to 2 km for the upper levels. The outer domain ($dx = 81$ km and $dt = 360$ s) was set up to cover the whole of Australia and the associated portion of the Southern Ocean down to approximately 60°S (Fig. 4). Four daughter nests were utilized (one-way nesting) with the innermost domain centered over central western Tasmania ($dx = 1$ km and $dt = 4$ s). The domain was chosen to incorporate as much of the large-scale dynamical features involved in the current analysis into the WRF grid with minimal information needed from the domain boundaries.

All simulations herein are 42 h in length and were initialized at 2200 local time (1200 UTC) with a minimum of 30-h spinup until the event of interest. Numerous experiments were utilized to investigate the optimal spinup time together with horizontal and vertical resolution; some of these results are mentioned in the following paragraphs. It was decided to use a longer spinup and larger outer domain as this configuration more accurately represented thermodynamic profiles from Hobart and off the west coast of Tasmania. This is in large part due to poor skill initial and boundary conditions within the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) final (FNL) dataset south of mainland Australia and over the Southern Ocean. The closest radiosonde station data assimilated into this data west of Tasmania and south of mainland Australia is Port-aux-Francais (49°S, 70°E), $\sim$5000 km west of Tasmania. This issue is explored further in section 4a.

The model was configured with shortwave radiation parameterized using Dudhia (1989) and longwave radiation as described in Mlawer et al. (1997). Boundary layer processes are represented using the Mellor– Yamada–Janjic scheme (Mellor and Yamada 1982) and interactions between the earth’s surface, boundary layer, and radiation schemes are parameterized using the Noah land surface model (Ek et al. 2003). Alternative parameterizations were investigated [e.g., the Betts–Miller–Janjic (Janjic 2000) convective parameterization scheme was implemented in the two outer domains and the Yonsei University (YSU) nonlocal boundary layer scheme developed by Hong et al. (2006) was also implemented]. These alternative configurations of the WRF...
model either underperformed or were no better than the standard configuration. It should be noted that model results presented herein were produced with no convective parameterization in the outer domains.

The TMP is used to describe cloud processes (Thompson et al. 2008). This scheme is a bulk microphysics parameterization that is double moment for ice and single moment for cloud water, rain, snow, and graupel. The number of cloud droplets (a proxy variable for CCN) activated upon reaching saturation is preset by the user; this was set to 75 cm$^{-3}$, consistent with direct measurements of CCN made at Cape Grim in northwest Tasmania (Gras 1995). Ice initiation is parameterized as described in Cooper (1986) and does not form until temperatures are $<-8^\circ$C or supersaturation w.r.t ice is $>8\%$. A more thorough investigation regarding the sensitivity of these simulations to microphysical parameterizations is the subject of ongoing research.

4. Evaluation

The model verification focuses mainly on cloud structure, with a brief examination of precipitation structure using radar. Comparisons with surface observations are not discussed, except to say that comparisons were evaluated and deemed fair. Satellite observations collected by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on the Terra satellite managed by the National Aeronautics and Space
Administration (NASA; Justice et al. 1998) are used in a broadscale evaluation. For the 2006 case study, model-simulated radar reflectivities are compared with observations from the West Takone radar site in northwest Tasmania. The radar data for 2007 were not available; no radar evaluation is possible for this event. Only a cursory examination of the radar data for the 2006 case is presented.

The principal observations used in the evaluation are in situ aircraft observations obtained by Hydro Tasmania’s (HT) cloud-seeding research aircraft, a Cessna Conquest, which flew between 2302 UTC 8 August 2006 and 0101 UTC 9 August 2006 and 2352 UTC 3 October 2007 and 0312 UTC 4 October 2007 (Fig. 3). The flight objectives were to encounter SLW between $-2.5^\circ$ and $-15^\circ$C for the purposes of cloud seeding. The aircraft had on board a Droplet Measurement Technologies (DMT) Cloud Aerosol and Precipitation Spectrometer (CAPS) probe (Baumgardner et al. 2001) that incorporates a hot-wire liquid water sensor, a Cloud Aerosol Probe (CAS) that measures particles within size range 0.5–50 $\mu$m, and a Cloud Imaging Probe (CIP) 25 $\mu$m–1.55 mm. Unfortunately no data were available for the CIP and hot wire on the CAPS during either case study. There were two additional hot-wire probes attached to the fuselage, a DMT and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) King hot-wire probe. In addition, the plane also collected thermodynamic measurements: relative humidity, temperature, and pressure.

### a. Atmospheric profiles

WRF-simulated soundings are produced both off the west coast of Tasmania (hereafter the upwind sounding) and over the central plateau (downwind) for comparison with in situ aircraft soundings (Figs. 5 and 6). The model soundings are produced at a single grid point, corresponding to the average latitude and longitude of the plane’s position during ascent. Averaging over a number of grid points was also investigated, but this did not notably affect the results.

The skill with which the model is able to represent upper-air soundings varies considerably between cases. The simulated 2006 upwind sounding (Fig. 5a) is able to recreate well both the temperature and moisture profiles in the lower atmosphere. The model-predicted ground
temperature is within 1°C of the observed and the model temperature trace lies over the measured trace between 900 and 750 hPa. The cloud base is close to the observed and the cloud top is within 20–30 hPa of the observed. A temperature inversion of \(\approx 2^\circ\)C is present in the model profile at around 730 hPa, but is not present in the observations. The downwind sounding for 2006 is shown in Fig. 5b. The observations show a neutrally stable atmosphere between 600 and 800 hPa. The model shows a neutrally stable atmosphere up to around 700 hPa then a large inversion is observed. The moisture profile resembles more closely the observations (see Fig. 5a).

Regarding 2007 the model (solid dark line in Figs. 6a,b) shows considerably less skill for a direct comparison. For both the up and downwind soundings the model overpredicts temperature and the moisture profile shows little resemblance to the observed. If, however the model sounding is delayed by 2 h both soundings better resemble the observed, suggesting WRF lagging behind the observations regarding the frontal timing. Further evidence supporting this claim is presented in the following section. Comparison of the delayed upwind model sounding shows that WRF over predicts temperature by approximately 1°C from the surface to approximately 350 hPa (top height of observations). A small temperature inversion is observed at 780 hPa that is not present in the observations. The model dewpoint profile is on average a few degrees above the observed. Qualitatively, the skill associated with the downwind profile shows many similarities with the upwind.

Wind profiles measured by the aircraft and model are also shown for both case studies on the right of Figs. 5 and 6. A notable feature observed during 2006 is the shear layer between 750 and 650 hPa. The largest value for this wind change is \(\approx 25\) m s\(^{-1}\) and occurs in \(\approx 100\) m at an altitude of 2.6 km. This phenomenon is also present with less magnitude during 2007. The model fails to reproduce this shear feature in either case study. GFS FNL reanalysis data were studied for the input thermodynamic and wind profiles used by WRF as initial and boundary conditions (see Figs. 7a,b). The observed wind shear is not found in this dataset. The reason for this midtropospheric shear remains unknown. In all, a total of seven aircraft soundings (during different events) have been examined over the west coast of Tasmania, this shear feature is clearly present in five and is the subject of ongoing research.
Throughout the vertical profile model winds have a maximum error of 15–20 kt with WRF tending to underestimate wind speed. Regarding 2006 the observed wind direction is from the northwest (280°), with the exception of the shear layer, the model has winds from the southwest (260°). The MSLP analysis in Fig. 1 indicates that at the time of the sounding the wind direction was transitory and changing from northwesterly to southwesterly. The difference in observed and modeled wind direction is due to WRF slightly leading the observations. WRF soundings produced 1 h earlier were from the northwest. Regarding 2007, the observed and modeled wind directions agree.

b. Satellite observations

Satellite-derived cloud-top temperature (CTT) from MODIS on the Terra platform is qualitatively compared with model CTT’s for domains 3, 4, and 5 (Fig. 8). A quantitative comparison is implemented for the finest resolution domain (domain 5). The algorithm used to derive satellite CTT is described in Platnick et al. (2003). The uncertainty in the satellite-derived CTT is an interesting problem: most recently Hanna et al. (2008) investigated the difference between satellite-derived CTT and upper-air measurements. Differences of approximately 5°C were common, the task here, however, is to simulate the brightness temperature that a satellite would observe. The algorithm employed uses the temperature of a cloud one unit of optical depth (τ) from the top of the model. Other assumptions are that the zenith angle is zero and cloud absorption coefficients are constant and dependent on specific hydrometeors. Hydrometeors assumed to contribute to cloud optical properties are cloud water, ice, snow, and rain; these are assumed to be present in sufficient numbers to affect cloud emissivity. The absorption coefficients are 0.145 00, 0.073 50, 0.002 34, and 0.000 33 m² g⁻¹, respectively (Dudhia 1989).

Figure 8 shows the planar view CTT for both cases, the observations, and the model. The observations for 2006 (Fig. 8a) show relatively cold CTTs associated with convective regions along the trough line over the western coast of Tasmania (see Fig. 1). East of this feature over the northeast portion of the island are cooler clouds (~240 K) associated with the trailing edge of the front. Figure 8b shows the frontal cloud band for 2007 over the
western region of Tasmania. This shows a cooler distribution of CTTs, however lacking the small localized regions of very cold clouds found in 2006. The simulated cloud field for 2006 (Fig. 8c) shows warmer clouds associated with the trough off the western coast of Tasmania, the position of this feature is well represented. The 2007 simulation (Fig. 8d) shows slightly warmer CTTs associated with the frontal cloud band, this feature is also well placed over the western portion of the island.

Figure 9 shows histograms of MODIS and model CTT for the finest resolution domain (domain 5). For both case studies, MODIS finds clouds warmer than 280 K that do not match WRF. Either MODIS is observing fog close to the sea level or inferring sea surface temperature as the cloud top. The soundings shown in Figs. 5 and 6 indicate that the cloud base is at 5°C; however, MODIS is indicating clouds at around 12°C, which is close to the temperature observed by the aircraft 100 m above the ocean surface and below the cloud base. Regarding 2006 (Fig. 9a), WRF underpredicts warmer clouds above 273 K, then overpredicts between 250 and 273 K. WRF fails to develop clouds with temperatures <245 K (i.e., WRF failed to reproduce the small number of very cold clouds associated with the trough line). The histograms for 2007 are more similar. Sensitivity studies suggest that small changes in the magnitude of absorption coefficients do little to alter the distribution of CTTs, increasing confidence in the model CTT algorithm.

Table 1 shows the mean, median, and standard deviation of CTT together with the total cloud fraction for each case study for the finest resolution domain. Cloud fraction is calculated by simply counting the number of grids that return a CTT at a level above the surface; this number is then normalized by the total number of grid cells within the domain. For the 2006 case the observed skewed distribution is highlighted by the difference in the mean and median CTTs, 261.47 versus 267.62 K respectively. WRF manages to replicate some of this, however, with a smaller magnitude, 266.98 versus 268.97 K. Cloud fraction is also underpredicted. Observations indicate that 94% of the domain is covered in cloud versus WRF’s 69%. (Note that the observed cloud fraction should be lower than 94% because of MODIS incorrectly classifying the sea surface as the cloud top). For the 2007 case WRF shows much greater skill. The largest error in mean (median) CTT is 2.3 (1.9) K and cloud fraction is better represented. WRF’s worst prediction is approximately 10% less cloud coverage relative to the observations.

c. Radar

The West Takone radar located in northwest Tasmania is a 5-cm C band. The minimum detectable signal...
is relatively high, in the range of 0–10 dBZ. Observed and simulated radar reflectivities for 1600 UTC 8 August 2006 are shown in Fig. 10. The method for determining the simulated radar reflectivity is described in Blahak (2007). At this time the frontal rainband is passing over the radar domain, enabling a comparison of planar and cross-section view precipitation core structure. The constant altitude plan position indicator (CAPPI) shown in Figs. 10a,b is at a height of 3 km, zonal cross sections along 240.5°S are shown in Figs. 10c,d (this latitude was chosen because of the clear view; mountains obstruct much of the view to the south).

The simulated radar reflectivities show maximum returns of ~22 dBZ, the observed is in the range of 24–28 dBZ. The finescale precipitation core structure is visually similar in the planar view; however, it is noted that this similarity could simply be due to chance. A simulated frontal rainband appears to the west of the observed indicating a possible temporal/spatial displacement of the simulated field. Cross sections show quite different vertical structure. The model replicates precipitation cores extending from the surface to around 5 km. However, it also shows midlevel precipitation not reaching the ground. This feature is not present in the observations.

The differences between the general shape of the model and observed reflectivity fields are expected. Inspection of the entire simulation (not shown), indicates that the model often shows differences regarding the spatial positioning of precipitating structures. Furthermore, WRF tended to underestimate large dBZ returns. Given the uncertainties in initial and boundary fields supplied to the model and the insufficient resolution of updrafts less than ~5 km in horizontal extent, it is unsurprising that differences exist.

d. Aircraft observations

The emphasis of this evaluation is on WRF’s ability to simulate aircraft-observed cloud structure within the finest-resolution domain (domain 5). Initially, a similar evaluation to that presented in Guan et al. (2001, 2002) and Vaillancourt et al. (2003) is carried out. This is a point-by-point direct comparison of aircraft-observed variables along the entire flight track with a virtual flight track. Observations of (i) temperature (°C), (ii) dew-point temperature, (iii) small hydrometeor particles (0.5–50 μm measured by the CAS), and (iv) liquid hydrometeors (measured with a hot-wire probe) are compared with model fields. The main evaluation, however, is more statistical and considers only the level flight tracks that were implemented by the aircraft while the seeding burners were aflame. These were conducted over the western region of Tasmania (see Fig. 3) for 2006 at an altitude of ~2.5 km between ~4° and 18°C and during 2007 at an altitude of ~2.7 km between ~8° and 11°C.

The method for obtaining the virtual time series was to input the aircraft trajectory in terms of latitude,
longitude, pressure, and time (for 2007 the virtual time series was delayed by 2 h in line with previous findings). The closest latitude, longitude, and time grid point from the model was then chosen and linear interpolation used with regard to the height coordinate. This was implemented with the same temporal resolution as the observations (1 Hz), that is, the same grid point is sampled a number of times. As the type of clouds sampled were predominantly cumulus cells having diameters of up to a few kilometers, comparisons along the entire flight track were made using numerous averaging length scales of 1, 2, 4, 8, 16, and 32 km.

The model-diagnosed variables used for comparison with small hydrometeor particles are cloud water content and small ice particle content ($q_c + q_i$) while for liquid hydrometeors, cloud and rainwater content are used ($q_c + q_r$). (Note: the model $q_i$ category includes diameters 11–125 $\mu$m, and is initiated with a density of 890 kg m$^{-3}$, this varies as a function of diameter and is approximately 660 kg m$^{-3}$ at $d = 50$ $\mu$m and 330 kg m$^{-3}$ at 100 $\mu$m.) Results presented here assume that all hydrometeors detected by the CAS are spherical and have a density of 1000 kg m$^{-3}$. This is considered a fair assumption for 2006 when less ice was present. For the 2007 event, however, the validity of this assumption is less robust as there were lower SLW contents and more ice. A lower bound on the bulk density of in-cloud “ice” measured using the CAS (0.5–50 $\mu$m) is postulated to be 400 kg m$^{-3}$ (the term ice refers to hydrometeors viewed by the CAS—these can be either water, ice, or both). Hence, for both case studies the “true” hydrometeor mixing ratio (as observed by the CAS) is postulated to be somewhere between what is presented here and a number that is 60% less. Hereafter, the discussion of small hydrometeor mixing ratios assumes that objects viewed by the CAS have a density of 1000 kg m$^{-3}$, unless otherwise stated.

It is noted that for ice particles >100 $\mu$m, the density is almost certainly lower than 400 kg m$^{-3}$ (Heymsfield et al. 2004a,b). However, within the present study the instrument used to measure ice particles only measures up to 50 $\mu$m. Furthermore, Heymsfield et al. (2004a) notes that for pristine ice crystals <100 $\mu$m, the density can be as much as 910 kg m$^{-3}$. Tasmania, lying within the northern Southern Ocean is considered to be pristine with very few natural CCN and little anthropogenic influence (Gras 1995). Hence, true ice (i.e., frozen hydrometeors <50 $\mu$m) particles observed by the CAS
could potentially have a density \(\sim 900 \text{ kg m}^{-3}\). Furthermore, as the model ice category is initiated with density of \(890 \text{ kg m}^{-3}\) and the aircraft measurements were made at temperatures \(\geq 20^\circ\text{C}\) where mixed-phase conditions are not only possible but were almost certainly encountered. The assumption that the true density of objects viewed by the CAS is between 400 and 1000 \(\text{ kg m}^{-3}\) is deemed suitable for a comparison of this nature.

This leads into a necessary discussion on the errors associated with measurements of liquid water using the CSIRO liquid water probe in mixed-phase conditions. Cober et al. (1995) found that in mixed-phase conditions the King liquid water probe responded to between 5\% and 30\% of ice water content, with an average response of \(\sim 20\%\). The uncertainty of the specific probe in use was not evaluated, hence, the uncertainty in liquid water contents presented herein is assumed to be that presented by Cober et al. (1995). The uncertainty in this quantity is of greater importance during the 2007 case due to its more mixed-phase nature.

Returning to the analysis of the virtual and observed aircraft measurements, regarding both case studies the variables that correlated best were temperature and dewpoint. Furthermore, this result was independent of spatial averaging, similar to results found in Guan et al. (2001). The correlations regarding the mixing ratios of small and liquid hydrometeors were less impressive. Regarding both case studies a clear dependence on spatial averaging was observed. In general, as the averaging length scale was increased the correlation increased. For temperature and dewpoint the correlation was always above 0.85 for 2006 and 0.9 for 2007. Regarding moist fields, at an averaging length scale of 1 km the correlation for both case studies was between 0 and 0.2. Averaging over 32 km the correlations increased, however all were \(\approx 0.65\).

The findings regarding the cursory comparison of the real and virtual flight tracks indicated that WRF was able to reproduce the measured temperature and dewpoint traces with a fair degree of accuracy, quantitatively similar to Vaillancourt et al. (2003), who found average correlations of temperature and dewpoint to be \(>0.9\) and \(>0.85\), respectively over 21 flights. The model’s ability to reproduce the hydrometeor traces was poorer, as was the case in Vaillancourt et al. (2003). As such, a further test is also employed where the observed mixing ratios along the seeding track are compared with those along a virtual seeding track. Both events presented here include at least four traverses of a seeding track, for 2006 there is only one seeding track. Regarding 2007 there were two seeding tracks. This analysis only considers the most northerly track as the aircraft made only two traverses of the southerly track.

The experimental procedure is to compare the 4 observational seeding tracks made over the course of approximately 1 h with 3 virtual seeding tracks each spaced 1 h apart (before, during, and after the observational period). The comparison is accomplished by averaging the aircraft data over 1 km (\(\approx 13\) s).

It is observed (Figs. 11 and 12) that the 2007 event contained smaller concentrations of SLW relative to 2006. Averaged over the entire seeding track, the 2006 event contained 0.070 \(\text{ g kg}^{-1}\) whereas the 2007 event contained 0.033 \(\text{ g kg}^{-1}\). Virtual seeding tracks are also shown. The model is able to qualitatively replicate the different SLW mixing ratios (i.e., the 2007 event contains approximately 50\% less SLW than the 2006 event). Quantitatively, however, the model overestimates SLW mixing ratios by \(\sim 300\%\) for both events (0.214 and 0.098 \(\text{ g kg}^{-1}\), respectively). Furthermore, the model tends to overestimate the spatial extent of liquid content regions (both case studies). Maximum SLW mixing ratios for 2006 are in close agreement, approximately 1.5 \(\text{ g kg}^{-1}\). For 2007, however, the model tends to underestimate maximum SLW mixing ratios; observations show peaks of \(\sim 1.0 \text{ g kg}^{-1}\) whereas the model maximum is \(\sim 0.5 \text{ g kg}^{-1}\).

Results regarding the analysis of small hydrometeors are shown in Figs. 13 and 14. It is noted that the average small hydrometeor mixing ratio during 2006 is approximately half that of 2007. Averaged over the entire seeding track the mixing ratio of all hydrometeors in the range 0.5–50 \(\mu\text{m}\) for 2006 is 0.077 \(\text{ g kg}^{-1}\) (similar to the value measured by the hot wire), for the 2007 case, 0.140 \(\text{ g kg}^{-1}\) (assuming 400 \(\text{ kg m}^{-3}\) these reduce to 0.029 and 0.056 \(\text{ g kg}^{-1}\), respectively). As before, model-derived virtual CAS traces for the three closest time periods to the seeding event are also shown. The model-predicted small hydrometeor mixing ratio for 2006 is 0.156 \(\text{ g kg}^{-1}\) (200\% more than the observed) and for the 2007 event 0.095 \(\text{ g kg}^{-1}\), well inside the uncertainty in the observed value.

It is noted that the seeding track average mixing ratio values for the hot wire and the CAS do not agree well for the 2007 case, but are in close agreement for 2006. This finding suggests that the 2006 case is a supercooled event, whereas 2007 is more mixed phase. The positioning of the observed peaks for SLW and small hydrometeors in Figs. 11a, 12a, 13a, and 14a correlate highly. The magnitude of the observed liquid water peaks for “lower” liquid water contents are often lower in magnitude than the CAS. Furthermore, for lower-magnitude liquid water peaks, the spatial extent is often greater for the CAS relative to the hot wire. The converse is true for “large” magnitude peaks.
Histograms showing the normalized frequency of occurrence for specific SLW and small hydrometeor mixing ratios during in-cloud conditions regarding both model and observations are shown in Figs. 11b, 12b, 13b, and 14b. In-cloud conditions for the observations are defined as liquid water or CAS hydrometeor mixing ratios greater than 0.01 g kg\(^{-1}\). In-cloud conditions for the model are defined as having cloud water mixing ratios greater than 0.01 g kg\(^{-1}\). The reason for choosing the cloud mixing ratio over ice mixing ratio as the indicator for model cloudy conditions is that the TMP has a tendency to produce low ice mixing ratios.
and hydrometeors tend to move rapidly from the ice to snow category as the diameter increases, which keeps ice mixing ratios low. Using the cumulative mixing ratio of all model moist scalars (including snow and graupel) to define in-cloud conditions was also investigated. This did not noticeably change the results.

The maximum SLW mixing ratio observed during the 2006 event (Fig. 11) using the hot-wire is $>1.3 \text{ g kg}^{-1}$ (13-s time constant). Averaged over 5-min intervals this remains $>0.3 \text{ g kg}^{-1}$. Approximately 55% of in-cloud conditions have SLW mixing ratios $\leq 0.3 \text{ g kg}^{-1}$ and $>15\%$ of in-cloud conditions have SLW $> 0.7 \text{ g kg}^{-1}$.

Regarding the CAS (Fig. 13), maximum hydrometeor
mixing ratios were 0.8 g kg$^{-1}$, approximately half of the value recorded using the hot wire. A potential reason for this discrepancy is that the CAS cannot detect particles >50 μm. Regarding the 2006 case, WRF predicted distributions of SLW and small hydrometeors closely resemble the observed. The Kolmogorov–Smirnov (KS) test (Massey 1951) was used to quantitatively assess the similarity of the distributions. The null hypothesis of the two samples being drawn from the same population could not be rejected at the 0.05 level for both liquid and small hydrometeors.

The maximum SLW mixing ratio observed during 2007 (Fig. 12) is ~0.9 g kg$^{-1}$. Here >80% of in-cloud conditions have SLW < 0.1 g kg$^{-1}$ and less than 10% of values are >0.2 g kg$^{-1}$. WRF-predicted distributions of liquid hydrometeor mixing ratios replicate qualitatively
the low SLW contents; however, the shape of the distributions are quite different. Approximately 50% of the in-cloud conditions have SLW < 0.1 g kg⁻¹, hence, underestimating the contribution of low liquid water content regions within individual clouds. WRF then overpredicts SLW mixing ratios between 0.1 and 0.5 g kg⁻¹. Applying the KS test to the distributions of SLW finds the two samples are not drawn from the same population. Regarding the comparison of small hydrometeors (Fig. 14b), WRF overpredicts the contribution of low hydrometeor content regions (<0.2 g kg⁻¹) and then underpredicts the contribution of higher mixing ratio regions. Here the KS test also finds the two samples to be dissimilar. To assess the sensitivity of this result to the bulk density, the lower value of 400 kg m⁻³ was used. In this case the observations do not show in-cloud regions with small hydrometeor mixing ratios >0.2 g kg⁻¹. This result still fails the KS test.

**Fig. 14.** As in Fig. 13, but for the October 2007 case study.
5. Evolution of mixed-phase clouds

This section investigates the evolution of mixed-phase clouds within the context of the WRF numerical simulations. The aims are first to quantitatively investigate the prevalence of SLW and ice over Tasmania and the ocean to the west, and second, to investigate the relationship between SLW, ice, and CTT.

Figure 15 shows the evolution of the total cloud fraction, mean, and median total frozen hydrometeor contents (TFH) and total SLW contents (TSLW, kg m⁻²). The time series over the 42-h simulations are taken for the finest resolution domain (Fig. 4), which consists of 373 × 394 1-km grids. TFH is defined as

$$\text{TFH}(i, j) = \sum_{k} [q_i(k, i, j) + q_s(k, i, j)] \rho \Delta H,$$

(1)

and TSLW as

$$\text{TSLW}(i, j) = \sum_{k} [q_c(k, i, j) + q_s(k, i, j)] \rho \Delta H.$$

(2)

Note that TFH is summed over all heights (k), whereas TSLW is summed over all k < 0°C. This is because of the existence of frozen hydrometeors at temperatures above freezing; supercooled water does not exist at temperatures >0°C. In Eqs. (1) and (2), i and j are the horizontal coordinates; q_i, q_s, q_c, and q_g are the mixing ratios of cloud, rain, ice, snow, and graupel; ρ is the fluid density; and ΔH is the height between η levels. Both TFH and TSLW are defined for in-cloud regions only.

For both case studies the first 12 h of simulation time are regarded as spin up. For 2006 the time series of cloud fraction (Fig. 15a) increases until 0300 UTC 8 August 2006. This first peak is associated with a prefrontal cloud band. About 12 h after this period (1200–1800 UTC 8 August 2006) cloud fraction (as defined in section 4b) reaches its maximum value of ~1. This is when the frontal cloud band (shown in Fig. 2) essentially covers the innermost domain. Afterward, cloud fraction falls to 0.4 then rebounds to >0.6 with the arrival of the post frontal air mass. The time series of TFH and TSLW (Figs. 15b,c) show the microphysical composition of clouds within the domain. Associated with the prefrontal peak in cloud fraction are clouds that contain similar masses per unit area of frozen and supercooled hydrometeors (~0.1 kg m⁻², i.e., potentially mixed phase). Then, associated with the main body of the frontal cloud band are clouds that are composed almost entirely of frozen hydrometeors. The mean and median values of TFH are similar at this time indicating that the majority of clouds have values of ~0.4 kg m⁻². As the trailing edge of the frontal cloud band enters the domain (~1800 UTC 8 August 2006) TSLW content increases and TFH content decreases. The final 6 h of the simulation
are entirely postfrontal. The mean TSLW is \(0.1 \text{ kg m}^{-2}\), the mean TFH varies between 0.0 and 0.2 \text{ kg m}^{-2}\, and the peak at \(-0100\ \text{UTC}\) is due to the arrival of the trough (see Figs. 1, 2, and 8a,c).

The 2007 event is shown to the right of Fig. 15. Total cloud fraction (Fig. 15d) shows quite a different situation to 2006. At 0000 UTC 3 October 2007, a postfrontal air mass exists within the domain. This continues until 1800 UTC 3 October 2007 when cloud fraction increases to a maximum of 0.9 due to the arrival of a front. Then 2–3 h before the end of the simulation the front exits the domain leaving a post frontal air mass. Throughout the entire simulation cloud fraction is between 0.6 and 0.9. The mean and median TFH and TSLW suggest that clouds are more likely to be mixed phase during this case. Between 0000 and 1800 UTC 3 October 2007 the mean TSLW is \(>0.1 \text{ kg m}^{-2}\) and the mean TFH is 0.2–0.6 \text{ kg m}^{-2}; however, the medians are small, \(<0.2\). This indicates that some clouds have large quantities of ice and/or water but the majority tends to have little quantities of both. The exception is after 1800 UTC 3 October 2007 as the frontal cloud band enters the domain. Here median TFH increases to 0.2 and TSLW increases to 0.05 \text{ kg m}^{-2}\.

Figure 15 suggests that the frontal cloud bands for both cases consist of mixed-phase clouds with median values of TSLW and TFH of \(~0.1\) and 0.2–0.4 \text{ kg m}^{-2}\, respectively. Furthermore, when taken over the entire inner domain mixed-phase conditions are also indicated to occur during pre-/post-frontal periods, however, with smaller quantities of liquid and frozen hydrometeors.

Figure 16 shows cross sections of total liquid hydrometeor mixing ratio \((q_i + q_s)\) and total frozen hydrometeor mixing ratio \((q_i + q_g + q_s)\) from domain 4 along 42°S for both case studies. The figure suggests that during pre-/postfrontal periods, clouds over the Southern Ocean and Tasmania are capped between 3 and 5 km, consistent with Mace et al. (2007). Figure 16a is during the frontal passage for the 2006 case and shows a relatively high freezing layer with large amounts of glaciated upper-level cloud \([\text{frozen hydrometeors (FH)} >0.5 \text{ g kg}^{-1}\)]. To the west of this feature are lower-level mixed-phase clouds with smaller quantities of FH \((0.05–0.5 \text{ g kg}^{-1})\) and SLW contents of \(1 \text{ g kg}^{-1}\). Figure 16b is during postfrontal conditions ahead of the trough and shows relatively little ice, large quantities of SLW \((1.5 \text{ g kg}^{-1})\), and a low freezing level \((\sim 1 \text{ km})\). Figures 16c,d show the 2007 case with moderate quantities of SLW \((0.5 \text{ g kg}^{-1})\) and ice \((0.5 \text{ g kg}^{-1})\), during postfrontal and frontal conditions, respectively. At the times shown for 2007 the cross sections imply that mixed-phase clouds exist. A further interesting feature regarding Fig. 16 is the relative heights of the inversion layer (indicated by the cloud-top heights) and the height of the freezing level. During pre- and postfrontal periods the 2007 case appears to have a higher inversion and a lower freezing level, relative to the 2006 case.
Instead of looking at domain-wide variables, Figs. 17 and 18a,c show time evolution histograms of the ratio of TSLW to TSLW + TFH over land and ocean, respectively. The time series has been separated into components over land and ocean to isolate any orographic effect the island of Tasmania has on cloud structure. Hereafter this ratio is referred to as the ratio of TSLW to all “cold” hydrometeors or RSACH, and is defined as

$$RSACH(i, j) = \frac{TSLW(i, j)}{TSLW(i, j) + TFH(i, j)}.$$  (3)

Using the above definition for RSACH, supercooled clouds are defined as having a RSACH > 0.7, mixed phase 0.3–0.7, and glaciated clouds <0.3. Figures 17 and 18b,d show the mean and median magnitude of TSLW and TFH over land and water, respectively. Regarding 2006, Figs. 17a,c show that for the majority of the simulation the probability of finding a RSACH close to zero for any grid point is high. This indicates that the majority of the time either no SLW exists or the mass of SLW is small compared to the mass of frozen hydrometeors. The exceptions to this statement are between 0000–0600 and 1800 UTC 8 August 2006 until the end of the simulation. The first period coincides with the arrival of prefrontal cloud. Here approximately 40% of grid points have a RSACH > 0.8 (i.e., 40% of the grid points contain 4 times as much TSLW as TFH) and approximately 12% of grid points have a RSACH of ~0.5 (i.e., mixed phase). Also observed at this time is an increase in the magnitude of the mean and median quantity of TSLW. After this period the frontal cloud arrives ~1200 UTC 8 August 2006. During this period the mean and median magnitude of TFH increases to a maximum over both land and ocean and the fraction of mixed-phase clouds increases once again.

An interesting feature at this time is the discrepancy between the TFH over land versus ocean. Over ocean the peak TFH increases to ~0.6 kg m$^{-2}$, over land the peak value is 0.4 kg m$^{-2}$. After the frontal cloud leaves the domain (~0000 UTC 9 August 2006) the mean and median magnitude of SLW decreases slightly over land and drops by one-half over ocean. At this time the probability of a cloud having a high RSACH increases. Over both land and ocean from 0300 UTC 9 August 2006 until the end of the simulation over 50% of cloudy grids in the domain are composed almost entirely of SLW. Previously mentioned regarding Fig. 15b was the peak in TFH at ~0100 UTC 9 August 2006, due to the
arrival of the trough indicated in Figs. 1, 2, and 8a,c. This feature is also present here. Figures 17a,c show that the trough arrives over ocean before land and is composed of clouds that contain a greater quantity of ice relative to clouds that exist earlier and later.

The 2007 event (Fig. 18) shows the passage of a front within the first 6 h of the simulation, during spin up. The second front occurs between 1800 UTC 3 October 2007 and 0000 UTC 4 October 2007; TSLW and TFH peak during this time. Throughout the majority of the simulation the probability of a cloud having a high RSACH is low. The highest chance of finding an entirely supercooled cloud is between 1200 and 1800 UTC 3 October 2007 (Fig. 18c). Greater than 30% of grid points within the domain are composed entirely of SLW. This is the prefrontal time period. The mean and median magnitudes of SLW are generally larger during this case and, in line with the previous case, always have greater magnitudes over land. Mixed-phase clouds are predicted by the model in the prefrontal period at 1800 UTC 3 October 2007 over land and in the frontal/postfrontal period between 0000 4 October 2007 and the end of the simulation over land and water. At this time clouds over ocean tend to favor more mixed-phase conditions with lower magnitudes of TFH and TSLW. Over land, clouds favor more glaciated conditions and contain larger magnitudes of both TFH and TSLW.

Regarding both case studies, WRF suggests that the probability of finding a mixed-phase cloud is much lower than the probability of an entirely glaciated or supercooled cloud. That said, for 2007 throughout the majority of the postfrontal period, approximately 12% of grid points have a RSACH of between 0.2 and 0.3. Cloud grids over land tend to favor more glaciated conditions with greater magnitudes of TSLW and TFH. This difference is not necessarily due to orographic effects; it could be the result of some synoptic forcing like the blocking pattern suggested by Pook et al. (2006).

Figure 19 shows time evolution histograms of CTT for both cases. The 2006 event (Figs. 19a,b) shows that between 0000 and 0600 UTC 8 August 2006, >50% (90%) of grid points have CTTs between $-10^\circ$ and $-5^\circ$C over land (ocean). This corresponds with the initial increase in both the RSACH and TSLW content of Fig. 17. Between 0600 and 1200 UTC 8 August 2006, high cold cloud associated with the frontal cloud band dominates

![Figure 17](http://journals.ametsoc.org/doi/abs/10.1175/2009MWR3011.1)
the domain. This cold cloud gradually moves to the east leaving the post frontal air mass with relatively warm cloud-top temperatures. Here over 80% of grid points have CTTs between \(-10^\circ\) and \(0^\circ\)C over land and ocean. Interestingly, clouds over the ocean show a clear preference for warmer tops (lower altitudes). Once again, the trough line that advects into the domain around 0100 UTC 9 August 06 is present here, demonstrated by the increase in cooler CTTs.

The 2007 event, Figs. 19c,d, shows a more homogeneous situation. Little difference in the distributions over land and water is observed. After spin up, the majority of cloud tops have temperatures between \(-5^\circ\) and \(-20^\circ\)C throughout much of the simulation. A small increase in cold clouds is observed after 1800 UTC 3 October 2007, associated with the second frontal cloud that advects into the domain. CTTs for this case are cooler and show greater variation. The exception to this statement is between 1200 and 1800 UTC 3 October 2007 (prefrontal) where over 40% of clouds over the ocean are between \(-10^\circ\) and \(-5^\circ\)C. This corresponds with a larger RSACH in Fig. 18c.

The results presented thus far suggest a relationship between CTT and mixed-phase conditions. Cloud fields with tops between \(0^\circ\) and \(-10^\circ\)C tend to contain predominantly SLW. This is demonstrated in both case studies. Cloud fields with a wider distribution of CTTs including cooler cloud tops tend to be more glaciated, but often contain larger TSLW and TFH contents.

6. Summary

According to the WRF simulations supercooled liquid water (SLW) exists in prefrontal, frontal, and post frontal air masses over the Southern Ocean and Tasmania, Australia. Simulated cloud-top heights are consistent with Mace et al. (2007). Absolute quantities peak within frontal cloud bands; however, the proportion of predominantly supercooled clouds is low; conversely the proportion of mixed-phase and mostly glaciated clouds is high. During pre–post-frontal periods SLW is present mostly in the absence of ice. The probability of a cloud having an equal mass of SLW and frozen hydrometeors (mixed phase) is low for all time, except within frontal cloud structures (i.e., the model has a tendency to produce either supercooled or glaciated clouds), mixed-phase clouds are rare.

There appears to be a relationship between the microphysical properties of a cloud, cloud-top structure, and vertical thermodynamic structure. Pre- and post-frontal air masses are found to contain low moisture–temperature inversions just above the freezing layer.
and convectively unstable boundary layers as shown in Figs. 5 and 6. Clouds developing in the unstable air are unable to penetrate the inversions, hence have narrow distributions of CTTs, which are close to the freezing level. These contain supercooled water and little ice.

Regarding 2006, during the pre- and postfrontal air masses the majority of clouds have tops between 0\degree C and −10\degree C due to strong moisture and temperature inversions in the model. The current method by which ice is initiated in the Thompson routine uses the Cooper parameterization (Thompson et al. 2008; Cooper 1986) and in general does not begin to move mass from the liquid to ice categories until temperatures are below −8\degree C, or the supersaturation w.r.t. ice is greater than 8%. During the prefrontal regime, supersaturations w.r.t. ice exceeded 8% at temperatures warmer than −8\degree C in approximately 3% of cloudy grids. Throughout the rest of the simulation generally less than 1% of cloudy grids met this criterion. Model-simulated clouds for this case study will always show large quantities of SLW and this finding should be relatively insensitive to changes in ice initiation parameterization, so long as ice does not initiate until cooler than −8\degree C. Essentially, the model cannot transfer mass from the liquid to the frozen categories until ice is initiated.

For the 2007 case, the inversion height is greater. The majority of clouds are able to obtain altitudes where temperatures are between −10\degree C and −15\degree C. Furthermore, a larger fraction of cloudy grids obtained supersaturations w.r.t ice >8% at temperatures warmer than −8\degree C, approximately 3% throughout much of the simulation, with a maximum of ~4%. These clouds spend a greater fraction of time transferring mass from the liquid categories to the frozen. This case study should be more sensitive to the ice initiation parameterization. If ice is initiated at a slower rate then a greater fraction of clouds will contain more supercooled water, should the rate of ice initiation increase the converse is true.

The results presented herein indicate that supercooled and mixed-phase clouds exist over this region of the world. The results indicate a correlation between atmospheric states possessing convectively unstable boundary layers and inversion heights close to the freezing level with supercooled cloud fields. The magnitude of supercooled water presented herein is consistent with earlier measurements presented in Ryan and King (1997). This research provides a physical basis for

![Histograms of simulated cloud top temperature for (a),(b) August 2006 and (c),(d) October 2007 case studies: CTT (a),(c) over land and (b),(d) over ocean.](https://journals.ametsoc.org/doi/abs/10.1175/2009MWR3011.1)
the long-term success of cloud seeding over this region, as detailed in an earlier paper by Morrison et al. (2009).

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