Mixed-phase clouds and precipitation in Southern Ocean cyclones and cloud systems observed poleward of 64°S by ship-based cloud radar and lidar

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Key Points:

- Generating cells at the top of mid-level mixed-phase clouds are commonly observed over the high-latitude Southern Ocean
- Supercooled drizzle is present in two of the three cases examined here with phase changes following supercooled liquid layer seeding
- Seeding of single-layer ice-precipitating supercooled liquid clouds occurs in the trailing clouds of each system

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Abstract

Mixed-phase clouds (MPCs), composed of both liquid and ice, are prevalent in Southern Ocean cyclones. A characterisation of these clouds on fine vertical scales is required in order to understand the microphysical processes within these clouds, and for model and satellite evaluations over this region. We investigated three examples of cloud systems collected by ship-mounted remote sensing instruments adjacent to East Antarctica at latitudes between 64°S and 69°S. These cases allow us to examine the properties of mid-level MPCs, with cloud tops between 2 and 6 km. Mid-level MPCs contain multiple layers of supercooled liquid water (SLW) embedded within ice during the passage of cyclones. SLW layers are capped by strong temperature inversions and are observed at temperatures as low as −31°C. Convective generating cells (GCs) are present inside supercooled liquid-topped mid-level MPCs. The horizontal extent, vertical extent and maximum upward Doppler velocity of these GCs were 0.6 – 3.6 km, 0.7 – 1.0 km and 0.5 – 1.0 m s^{-1}, respectively, and are consistent with observations from previous lower-latitude studies. Ice precipitation is nearly ubiquitous, except in the thinnest clouds at the trailing end of the observed systems. Seeding of lower SLW layers from above leads to periods with either larger ice particles or greater ice precipitation rates. Periods of supercooled drizzle lasting up to two hours were observed toward the end of two of the three cyclone systems. This supercooled drizzle turns into predominantly ice precipitation as the result of seeding by ice clouds located above the precipitating SLW layer.

1 Introduction

Mixed-phase clouds (MPCs) containing both ice and liquid occur commonly from the tropics to the polar regions (e. g. Hogan et al. (2003); McFarquhar et al. (2007); Hu et al. (2010); Mioche, Jourdan, Ceccaldi, and Delanoë (2015)). These clouds remain difficult to model correctly due to the interplay of microphysical and dynamical processes which regulate their formation, maintenance and decay (Sotiropoulou et al., 2016), and because the scales over which these processes occur are substantially smaller than the resolution of climate and weather prediction models. The observed longevity of MPCs indicates that the removal of ice crystals from the cloud through gravitational sedimentation must be balanced by a continuous source of liquid water. Intra-cloud processes including updrafts and turbulent mixing, or a continuous supply of new liquid at cloud base, must be sufficient to replenish the liquid water (Rauber & Tokay, 1991; Koroloev

& Field, 2008). The correct modelling of cloud phase partitioning between ice and liquid water is necessary to match observations of reflected shortwave radiation (Forbes & Ahlgrimm, 2014; Kay et al., 2016; Tan et al., 2016; Lenaerts et al., 2017). Cloud phase was recently shown to strongly influence Antarctic ice shelf surface melting (Gilbert et al., 2020). The presence of multi-layered MPCs reported in the extra-tropics indicates that these clouds can exist and persist in a complex environment (Verlinde et al., 2013). Initiation of upper (or free-tropospheric) MPC layers are often due to large scale advection of moisture, while MPC layers closer to the surface are also influenced by surface processes such as heat and moisture fluxes and turbulence. (Luo et al., 2008)

The upper part of an idealized mid-level MPC (which we refer to here as being those clouds with tops between 2 km and 6 km altitude and temperatures between $-10°C$ and $-30°C$) often consists of a thin supercooled liquid water (SLW) layer of thickness less than about 300 m (Hogan et al., 2003; Ansmann et al., 2009; Barrett et al., 2020), beneath which supercooled drizzle and/or ice precipitation may be present. The depth of this precipitating layer depends upon the depth of ice supersaturation but is usually much greater than the thickness of the SLW layer itself (Rauber & Tokay, 1991). The liquid nature of these cloud tops results in strong radiative cooling by reflecting incoming shortwave radiation and emitting longwave radiation (Heymsfield et al., 1991; Hogan et al., 2003). The longwave emission produces strong cooling at cloud top that initiates turbulent mixing driven by the negatively buoyant air parcels and a large temperature inversion is observed at cloud top height due to this turbulent mixing and radiative cooling. Ice particles are formed inside the liquid layer through heterogeneous freezing and secondary ice production processes and grow rapidly by vapor deposition, riming and aggregation. Another temperature inversion may be evident at the base of the ice virga layer due to latent cooling as the ice particles sublimate in a drier air mass (Forbes & Hogan, 2006). It remains unclear whether this idealized description is applicable to MPCs found over the Southern Ocean and coastal Antarctica due to a lack of observational data.

MPCs are present throughout the lifecycle of extra-tropical cyclones, both within ice clouds (of several kilometers vertical extent) and in post-frontal boundary-layer clouds (Field et al., 2004; Jackson et al., 2012; Noh et al., 2019). Generating cells (GCs) and their associated fall streaks occur frequenctly within extra-tropical cyclones and are important for understanding surface precipitation due to their role in ice production (Kumjian et al., 2014; Cunningham & Yuter, 2014; Plummer et al., 2015; Keppas et al., 2018). These

GCs are small regions of convection located at or near cloud top, and exhibit relatively large updraft speeds (of the order of $1 - 2$ m s^{-1}), and a confined vertical and horizontal extent ($1 - 2$ km and less than a few kilometers, respectively) (Rosenow et al., 2014). These GC characteristics are consistent between cyclones, but on the other hand the temperature and altitude at which GCs occur can vary markedly (Kumjian et al., 2014). Aircraft observations of generating cells over the Southern Ocean (between 43°S and 61°S) revealed a mean horizontal scale of around 400 m (Y. Wang et al., 2020), which is lower than mean Northern Hemisphere GC scales.

Satellite and surface-based observations suggest that SLW clouds and low-altitude SLW-topped MPCs are particularly common in the Southern Ocean compared to other regions of the world (Ceppi et al., 2016; Choi et al., 2014; Marchand et al., 2009; Storelvmo et al., 2015; Hu et al., 2010; Kanitz et al., 2011; A. E. Morrison et al., 2011; Huang et al., 2012), and are likely more common than above oceans in the Northern Hemisphere at similar latitudes (Ceppi et al., 2016; Choi et al., 2014; Huang et al., 2014; McCoy et al., 2014). This may be due to the relatively low ice nucleating particle (INP) concentration in this region (Burrows et al., 2013; McCluskey et al., 2018), which inhibits primary ice production within the clouds and could restrict precipitation. The ubiquity of low-level cloud over the Southern Ocean (Haynes et al., 2011; Marchand et al., 2009) makes understanding boundary layer cloud processes and microphysics from space challenging, because satellite-based products suffer from phase uncertainty beneath cloud top height, especially in the presence of multiple cloud decks (Mace, 2010). Surface-based remote-sensing and in-situ observations are therefore required to quantify cloud properties and complement the satellite observations (Listowski et al., 2019). Recent campaigns have begun to address the paucity of these data over the Southern Ocean by employing aircraft (Chubb et al., 2013; Huang et al., 2015) and ship-based platforms (Protat et al., 2017; Mace & Protat, 2018a; Alexander & Protat, 2019; Kuma et al., 2020; Klekociuk et al., 2020) to quantify cloud, aerosol, and precipitation properties, and evaluate models and satellite retrievals.

Although characterisation of MPCs in the Arctic using surface-based active remote sensors is further advanced than at high Southern latitudes (e. g. H. Morrison et al. (2012); Verlinde et al. (2013)), it is unlikely that the results from the Arctic are translatable to the Southern Ocean and coastal Antarctic region due to differences in aerosol concentrations, meteorology and surface forcing. The Southern Ocean is characterised by strong

surface winds and the continuous passage of extratropical cyclones and associated frontal cloud systems throughout the year. The winds experienced along and adjacent to much of coastal East Antarctica are a mixture of local katabatic forcing from the interior of the continent, and intermittent strong north-easterly winds associated with the passage of warm fronts from the cyclones centred in the storm track further north (Turner et al., 2009; Orr et al., 2014; Alexander et al., 2017). Correct cloud phase representation is also necessary for correctly modelling snow melting along the Antarctic coastline (King et al., 2015; Gilbert et al., 2020).

In this study, we examine aspects of clouds and precipitation in three extra-tropical systems which were located close to the East Antarctic coastline. The clouds in the warm and cold sectors of two cyclone passages are examined for two of these cases, while the third case is an example of an extensive cloud system formed in the presence of a weak trough. We use observations collected by a suite of instruments deployed aboard an ice-breaking ship during the Measurements of Aerosols, Radiation and Clouds over the Southern Oceans (MARCUS) campaign to determine characteristics of generating cells, mixed-phase cloud occurrence, and precipitation phase. Such characterisation, and the identification of the synoptic-scale forcings and the thermodynamic environment in which MPCs exist, is necessary if we are to understand their presence, prevalence, evolution and endurance over this near-coastal region. Section 2 describes the data used. We examine the three systems in detail in Section 3, including their generating cells and precipitation phase. The results are then discussed and related to prior observations in Section 4 before the conclusions in Section 5.

2 Data and analysis

The MARCUS project installed instruments from the DoE Atmospheric Radiation Measurements (ARM) Mobile Facility 2 (AMF2) aboard the Australian icebreaking vessel *RSV Aurora Australis* between November 2017 and March 2018 (McFarquhar et al., 2021). A comprehensive suite of instrumentation collected data during three transits between Australia and Antarctica, and one between Australia and Macquarie Island, during the summer season. The MARCUS instrumentation used in the present study are summarised in Table 1.

All data analysed in this study were acquired during the third *RSV Aurora Australis* voyage (V3) of the summer season. MWACR data are calibrated by adding 4.5 dB to the reflectivity profiles provided by ARM. This value was deduced from evaluations of the MARCUS MWACR reflectivity against the calibrated W-band cloud radar onboard the CAPRICORN-II voyage over similar latitudes and times (Mace et al., 2021), and is consistent with the ARM cloud radar offsets identified by Kollias, Treserras, and Protat (2019). The MWACR was mounted on a stabilizing platform which helped ensure that it remained vertically pointing, although as we will detail below, the ship's heave, pitch and roll during the three case studies was minimal.

Raw 532 nm backscatter return signals from the MPL are processed to remove background noise, corrected for beam overlap, and are then calibrated using lidar signal from aerosol-free regions above the boundary layer, following Alexander and Protat (2018). Cloud base and vertical extent (up to the limit of lidar signal attenuation) are calculated from the calibrated backscatter and depolarisation ratio profiles following the return signal gradient algorithm described in Z. Wang and Sassen (2001). Uncertainty in cloud base height is due to the inherently noisy nature of the backscatter gradients, which is reduced by vertically smoothing the backscatter profiles with a five-point smoothing function. This smoothing is performed prior to determining the maximum gradient in backscatter, which we assign to be the cloud base height. Cloud phase is determined using the results from Hu et al. (2010), including accounting for horizontally-oriented ice plates because the MPL points vertically. We firstly determine cloud base height, vertical extent and phase of those clouds which exceed a large backscatter gradient threshold at cloud base (note that there is little sensitivity to the actual threshold value set). These clouds are predominantly, but not exclusively, liquid water. We then separately calculate cloud base height, vertical extent and phase of clouds which have small backscatter gradients at cloud base. This method successfully identifies multiple SLW layers embedded in MPCs, which are often visible in the raw lidar data over the high latitude Southern Ocean. The inferred cloud top height may be lower than the true cloud-top due to lidar signal attenuation, but (as we will find later) the total amount of liquid water and attenuation is often small in these mid-level MPCs in the abscence of precipitation.

We perform a Monte Carlo simulation using a random population of $N = 1000$ samples from a normally-distributed population in order to quantify the uncertainty of attributing the cloud phase (e. g. Alexander, Klekociuk, McDonald, and Pitts (2013)).

For each integrated cloud attenuated backscatter β_{int} and integrated depolarisation ratio δ_{int} point, we have an associated uncertainties $\Delta\beta_{int}$ and $\Delta\delta_{int}$, which we set to be twice the standard deviation of the normal distribution. We then determine the cloud phase for each of these 1000 realisations. These simulations indicate that we misclassify around 1% of the SLW as ice across the total of eight days of lidar observations used in these three case studies.

We also use data from the 1290-MHz Beam-Steered Radar Wind Profiler (BSRWP) in order to characterise the horizontal wind field. These data are available at one-hour temporal resolution and at a maximum altitude of 5 km, although data gaps in the upper altitudes are not uncommon. Radiosondes were launched every six hours from the ship for the entire summer campaign, providing a unique and valuable upper-air dataset over the Southern Ocean and sea-ice zone (Sato et al., 2018). The radiosonde data are used for investigating the detailed thermodynamics during SLW and virga cases. Data from a two-channel microwave radiometer (MWR) are used to calculate liquid water path (LWP) and precipitable water vapor (PWV) (Marchand et al., 2003). ERA5 (European Centre for Medium-Range Weather Forecasting: Reanalysis Fifth Generation) (Hersbach et al., 2020) thermodynamic data at the native resolution of $0.25° \times 0.25°$ from the nine closest grid-cells to the ship's location are interpolated to provide the vertical temperature profiles above the ship.

The primary objectives of V3 were to conduct the annual victualling resupply of Mawson station (67.6°S, 62.9°E) and retrieve summer personnel at Davis station (68.6°S, 78.0°E). We investigate three events when the ship was south of the oceanic polar front and close to East Antarctica. The area of East Antarctica relevant for this study is shown in Figure 1. The location of both stations, the ship's track into Davis and the locations of the radiosonde launches made during the three case studies are indicated. The February 2018 mean sea ice concentration from ERA5 reveals remant sea ice present offshore from Mawson during this period. The sea conditions were calm during the sampling periods, with the small amounts of remnant first-year sea-ice acting to damp most ocean swell. We discuss details of the ship's heave, roll and pitch in the case study analyses below.

3 Results

3.1 Case 1: Voyage into Davis (64°S – 69°S) on 25 - 26 January 2018

3.1.1 Overview of event

The METOP-A satellite image of the regional cloud structure and the ERA-5 500 hPa geopotential height at 04 UT 26 January is shown in Figure 2, which is a time near the start of this case study. A ridge of high pressure extends southward from the mid-latitudes, with a weak shortwave trough to the west of the ship supporting extensive mid-level cloud cover above the ships track. This large-scale mid-level cloud system propagated eastwards over the course of the 26 January and was replaced by a homogeneous cloud layer with lower cloud tops above the ship's track (not shown). A cyclone is developing far to the west of Davis, upstream of this blocking ridge.

The cloud phase and background thermodynamic structure as observed by the MARCUS instruments onboard *RSV Aurora Australis* as the ship transited into Davis on 25 – 26 January 2018 are summarised in Figure 3. Solar midnight is around 19 UT at the longitude of Davis. Shallow low-level mixed-phase clouds are seen between 18 UT 25 January and 03 UT 26 January as the ship traversed latitudes 64°S – 65°S. These are typical of the duration, mixed-phase and vertical extent of boundary-layer clouds observed at lower latitudes over the Southern Ocean (Mace & Protat, 2018a; Noh et al., 2019). The hourly horizontal wind field from the BSRWP reveals a predominantly westerly flow up to the 5 km limit of wind detection. Deep precipitating ice clouds are evident between 06 UT and 14 UT 26 January. Liquid layers (if present) could not be detected during these times due to attenuation of the lidar signal. Surface temperatures do not exceed freezing throughout the event. Radar reflectivities are noteably lower after 14 UT 26 January and multiple SLW layers embedded within ice become evident after 16 UT 26 January. Weakening southwesterly winds of less than 10 m s^{-1} predominate inside these trailing clouds. Attenuation of the lidar signal by low clouds means that it is only sporadically possible to detect liquid in the upper layer (between 3 and 4 km), although it seems likely that a liquid layer persists throughout. Liquid water path decreases from 12 UT 26 January onwards as the radar reflectivity drops and cloud base height rises.

3.1.2 Generating cells

Figure 4 shows the period 17 – 18 UT 26 January and reveals the intricate structure of these clouds on fine temporal and spatial scales. Convective generating cells are present in the upper-level cloud region (2.3 – 3 km altitude) above the middle SLW layer. The MPL detects the 3 km cloud top prior to 1715 UT, before lower-level SLW layers become too optically thick. Ice is forming in the coldest, highest parts of the SLW layer, in this case at temperatures around $-13°$C. Ice fall streaks are readily visible in the MWACR reflectivity. Thickening of the lowest-level SLW layer inhibits identification of the SLW at upper levels after 1730 UT due to the near-full attenuation of the lidar signal. The uppermost SLW layer is present (where detectable by the MPL) inside and between GCs. This is consistent with aircraft observations which indicated minimal difference between liquid water content inside and between GCs over the open Southern Ocean (Y. Wang et al., 2020).

The temperature, relative humidity and wind speed and direction measured by a radiosonde launched at 1732 UT and passing through these multi-layered SLW and ice virga are shown in Figure 5. A well-mixed layer, capped by a 3°C temperature inversion at SLW cloud top height, is seen in the profile of the potential temperature θ between 2.6 km and 3.1 km altitude. This altitude corresponds to the convective generating cell region identified previously between the two uppermost SLW layers. Weak wind speeds of < 5 m s^{-1} are present inside the cloud at altitudes below about 2.3 km, but increase to 10 m s^{-1} at cloud top. Liquid layers near 1.5 and 2 km are associated with weak temperature inversions. The θ increases inside the ice virga (above 0.5 km altitude), consistent with warming of the environment by longwave absorption by precipitating ice. The lowest-level SLW layer is capping the boundary layer (compare with Figure 4) and may be coupled with the ocean surface.

We show the MWACR reflectivity between 1719 – 1737 UT 26 January in Figure 6a, with GCs clearly visible throughout the interval. The MWACR's Doppler velocity (i. e. the sum of particle fall speed and vertical air motion) is displayed for this interval in Figure 6b. The ship's speed over ground (seafloor) was 7 m s^{-1}, heading 175° and the pitch and roll were always $< 0.2°$ during this time. We display the Doppler velocity profiles which have not been corrected for the ship's heave because this is negligible. Specifically, during the time interval shown in Figure 6b, the root-mean-square (rms) of the heave

velocities (which were sampled at 10 Hz) was 0.07 m s^{-1}. Individual generating cells (GCs) occur in the upper part of the cloud, with a vertical extent of 0.7 – 0.8 km. Doppler velocities reach 1.0 m s^{-1} directly above the 2.5 – 2.6 km SLW layer and are close to 0 m s^{-1} at cloud top altitude of 3.1 km. The Doppler spectra is shown in Figure 6c for data collection starting at 1728 UT and lasting 2 s, which is in the middle of a convective GC. A bimodal structure is evident around 2.3 km altitude, with a secondary peak in the spectra evident at 0 m s^{-1}. This is indicative of a population of SLW droplets and corresponds to the SLW layer as visible in the MPL data. A wavelet analysis on time-series of reflectivity within the GCs indicates that these predominantly had a duration of around 2 minutes (not shown). Given the motion of the ship at this time, and the prevailing wind speed within the clouds of 5 m s^{-1} from 240° (from Figure 5), we estimate the horizontal extent of these convective cells to be about 1.2 km.

3.1.3 SLW layers and precipitation phase

Figure 7 shows the last seven hours of this event. Three separate SLW layers are identifiable between 1.5 km and 3 km altitude after 1630 UT. There is an increasing distance between the top two SLW layers, perhaps due to thermally induced circulations within the cloud driven by cloud top radiative cooling. The low volume depolarisation ratio δ_v below SLW cloud base indicates that supercooled drizzle is likely falling out of these clouds prior to 17 UT. This precipitation phase transitions to be predominantly ice after 1730 UT: the δ_v below SLW cloud base increases and the LWP decreases to values close to zero which indicates insufficient liquid water for the precipitation to be drizzle. After 2030 UT, ice precipitating out of the SLW layer above 3 km sublimates before reaching the SLW layer located at 2 – 2.3 km altitude.

The MWACR reflectivity is larger in the ice clouds below 2 km between 1730 UT and 1930 UT than before 1730 UT, which corresponds to the time when ice falling from the highest SLW layer intercepts the second SLW layer. This increase in reflectivity can either be due to an increase in ice particle size (through riming), or an increase in ice concentration. The increased reflectivity coincides with vertically continuous observations of ice from the supercooled liquid cloud top at 3 km altitude down through all the SLW layers, i. e. seeding of the lowest boundary-layer coupled SLW cloud layer by ice produced in the generating cells at cloud top. Note that the MWACR reflectivity indicates the presence of some ice within the drizzle prior to 1730 UT.

3.2 Case 2: Passage of a cyclone above Mawson on 11 – 13 February 2018

The *RSV Aurora Australis* spent nearly two weeks at Mawson for the annual station resupply. During 'daytime' operating hours, the ship was moored in the harbour adjacent to the station. During local 'night' (solar midnight is around 20 UT), or during periods of inclement weather, the ship repositioned a few nautical miles offshore. This small variation in position is insignificant for our analysis of synoptic-scale cloud systems associated with two consecutive cyclones whose centers passed north of Mawson. Broken pack-ice was still present offshore of Mawson during these two weeks, with a coastal polynya keeping the near-shore region largely ice-free.

3.2.1 Overview of event

The first cyclone passage studied over Mawson occurred between 11 – 13 February 2018. Figure 8 shows the satellite image of the synoptic cloud field and 500 hPa geopotential height at 04 UT 13 February, which is a time toward the end of this event. The cyclone was centred around 64°S during these three days and weakened as it propagated from west of Mawson station to a position north of Davis by 04 UT 13 February. Earlier satellite images and ERA-5 thermodynamic fields reveal a warm front preceding the cyclone's passage, while the cold front associated with this cyclone remained far to the north of the continent (not shown). The Patchy low and mid-level clouds are visible directly offshore of Mawson at 04 UT 13 February in Figure 8 in the cold sector of the cyclone, which will be discussed in detail below.

The radar reflectivity and thermodynamic profiles during the event are shown in Figure 9. Low-level wind below 1 km altitude is likely a mix of the synoptic-scale winds and an enhancement in the katabatic winds. Indeed, such wind structure observed at the East Antarctic continental margin is typically observed during the passage of offshore cyclones (Orr et al., 2014; Alexander et al., 2017). SLW layers observed by the lidar at 4 - 5 km altitude near the start of the event (14 - 16 UT 11 February), along with strong westerly winds, correspond to the warm conveyor belt and the warm front as identified along coastal East Antarctica (Jullien et al., 2020). Radar reflectivity decreases and cloud top height lowers after 12 UT 12 February with evidence of multiple SLW layers within the ice clouds. MODIS Aqua retrievals (MYD06) near 10 UT on 12 February indicate the cloud-top phase is liquid, with a total column optical depth between about 15 and

30 (not shown). The MARCUS MPL is heavily attenuated at this time, and is unable to detect SLW at cloud top. While it would not be surprising (given the frequent presence of SLW near cloud top), it is ambiguous as to whether or not there is liquid water at cloud-top at this time or whether MODIS is responding to the the liquid further down in the cloud. A single-layer MPC persists in the light wind conditions at 2 km altitude after 00 UT 13 February, consistent with MODIS Terra imagery that shows thin and somewhat patchy clouds near 05 UT on 13 February (not shown; MOD06 retrievals were largely unsuccessful at this time). Note the presence of a thick ice cloud centred on 02 UT 13 February which is precipitating into the SLW. We will discuss this event in Section 3.2.3.

3.2.2 Generating cells

Convective GCs are present during Case 2: the radar reflectivity and Doppler velocity between 1541 – 1559 UT 15 February are shown in Figure 10, along with the spectra at 1544 UT. Upward motions reaching up to 1.0 m s^{-1} are present with 0.5 km of cloud top. The temporal scale of these GCs calculated from a wavelet analysis (not shown) varies between 2 –3 minutes. If we assume that the wind speed at cloud top height of these GCs is 20 m s^{-1} (the value taken from the closest radiosonde profile, launched at 1732 UT 11 February), the spatial scale of these GCs is 2.4 – 3.6 km. The thick ice clouds fully attenuated the lidar signal (not shown) thus we have no information on the presence or absence of SLW within these GCs, but microwave radiometer data indicates that liquid water is present during this time.

3.2.3 SLW layers and precipitation phase

Figure 11 shows details of the clouds observed toward the end of the Case 2 cyclone. Similar to the observations made of Case 1 (the transit into Davis), multiple layers of SLW clouds are apparent, although it is difficult to identify the SLW layer at ice cloud top before 18 UT 12 February due to opaque lower-level SLW layers. The SLW layer around 3 km altitude ascends in time and corresponds to a narrow vertical band with a decrease in MWACR reflectivity (most clearly visible in Figure 11a directly after the 1800 UT SLW layer, or directly before the 1930 UT SLW layer).

A layer of SLW with base around 2 km is identified throughout this part of the event. The δ_v beneath this SLW layer (Figure 11c) indicate the presence of supercooled driz-

zle between 00 – 02 UT 13 February. The sudden increase in δ_v below the SLW layer after 02 UT 13 February indicates the dominance of precipitating ice, although we cannot rule out the possibility of small amounts of supercooled drizzle also being present. The liquid water path (Figure 11d) is large enough to support the existence of supercooled drizzle during this time. The observation of precipitating ice between 0200 - 0330 UT matches the intersection of the 2 km altitude SLW layer by a high-level ice cloud (Figure 11a).

The two radiosonde profiles obtained during this interval (Figure 12) indicate an inversion layer at cloud top height (an inversion of 3°C at 4 km at 1730 UT; and 4°C at 2.5 km at 2332 UT). The θ profile below cloud top indicates a well-mixed region inside the MPC at 2332 UT. A shallow, well-mixed near surface layer due to the katabatic wind is apparent at 2332 UT. The strong wind shear above the jet may be an intense source of mixing.

3.3 Case 3: Passage of the following cyclone above Mawson on 14 – 16 February 2018

3.3.1 Overview of event

The following cyclone also passed north of Mawson and produced cloud bands visible above the ship from 14 – 16 February 2018. Mid-level ice seeding and a single SLW layer precipitating ice at temperatures below −30°C will be described, but for this case we find no evidence of supercooled drizzle, which is in contrast to the two prior case studies. The imminent arrival at Mawson of the cyclone's warm front and associated cloud bands are visible in the satellite cloud image and geopotential height data at 19 UT 14 February in Figure 13. The cold front associated with this cyclone, as with the previous Mawson cyclone, remained well to the north of the continent (not shown, see Vignon et al. (2021) for further details). Satellite images and thermodynamic data from later times indicate that this cyclone weakened as it propagated south-eastward toward the coast, with cloud dissipating in a mid-level westerly flow on 16 January (not shown).

Boundary-layer mixed-phase clouds are present before 20 UT 14 February, preceding the arrival of the warm front. A mixed-phase cloud (liquid water layer at 5.7 km precipitating ice virga) is present from 16 UT 14 February (Figure 14). These high-level SLW clouds are commonly observed over the Southern Ocean (McFarquhar et al., 2021). This

mixed-phase cloud descends in time, maintaining cloud top temperatures of about −30°C. Liquid water path (LWP) is much larger when shallow boundary-layer mixed-phase clouds are observed than when only the mid-level SLW layer is present. The horizontal wind field within the ice remains light (at least at altitudes below 5 km, which is the maximum range of the BSRWP). Similar to the previous case study, winds above 4 km altitude veer from north-westerly to northeasterly and the temperature rises above 3 km altitude as the cloud base height decreases. The winds and SLW clouds again indicate the presence of a warm front, following the model of Keppas et al. (2018). Thick ice clouds persist until around 06 UT 16 February, well after the surface pressure starts to rise. Single layers of SLW cloud occur in regions of light wind from about 11 UT 16 February onward.

3.3.2 Generating cells

The radar reflectivity, Doppler velocity and spectra of the GCs present between 1039 – 1057 UT 15 February are shown in Figure 15. The thick ice clouds fully attenuated the lidar signal (not shown) thus we have no information on the presence or absence of SLW within these GCs, but microwave radiometer data indicate the presence of liquid water. The Doppler velocities are displayed without correction for the negligible heave velocities during this time interval: the rms heave velocity during this time was 0.004 m s^{-1}. The overall features of the GCs seen in this event are consistent with those reported in Case 1 and Case 2. GCs have vertical extent around 0.9 km, fall streaks are clearly evident, and the wavelet spectra indicate dominant temporal scales of 1 minute and 3 minutes (not shown). Wind speeds at cloud top height were around 10 m s^{-1} (obtained from the 1130 UT radiosonde profile, not shown), thus the spatial scale of these GCs varied from 0.6 – 1.8 km during this interval. The Doppler velocity spectra at 1048 UT, in the middle of a GC, indicate velocities around 0 m s^{-1} between cloud top and about 4.1 km altitude, with the falling (negative velocities) particles clearly evident at lower altitudes. The bi-modality around 3.8 km altitude (at the base of the GCs) suggests the presence of a second SLW droplet population.

3.3.3 SLW layers and precipitation phase

Figure 16 shows the clouds and precipitation observed toward the end of the passage of the Case 3 cyclone. Although thick, low-level SLW cloud identified in the MPL

data before 10 UT mostly obscures the clouds at higher levels, we can see that SLW clouds exist above 4km at temperatures as low as −31°C. There are two distinct high-altitude SLW cloud layers just above, at 07 UT, separated vertically by about 500 m. The highest SLW layer does not appear to be precipitating. Likewise, a careful examination of the low-level SLW clouds suggests that there are two SLW layers here.

After 11 UT, a precipitating SLW cloud layer persists for two hours at an altitude of 4.2 km and cloud top temperature of −31°C. Retrievals from MODIS Aqua taken near 11 UT and MODIS Terra near 0530 UT on 16 February (MYD/MODIS products) both indicate the region near the ship covered by primarily liquid phase clouds with a cloud-top near 4 km, along with some smaller patches of ice cloud (not shown). Liquid particle effective radius was near or below 10 μm, with lower overall optical depths during the overpass near 11 UT, all of which is consistent with the radar and lidar observations. The δ_v (Figure 16c) indicates the predominance of ice precipitation beneath this mid-level cloud. Streaks of ice from higher altitudes (visible in the MWACR data in Figure 16a) intercept this SLW layer on occasion, which act to seed the SLW layer. These seeding events may be a factor in the decay of the SLW layer. The radiosonde launched at 1130 UT (Figure 17) passed through this virga and SLW layer: the stable top above the SLW layer around 4.5 km altitude is clearly evident. The thermodynamic profiles below 0.5 km altitude again show the typical characteristics of the katabatic wind at Mawson (Vignon et al., 2019). The well-mixed convective boundary layer tops out around 1.7 km, which corresponds to cloud virga base. The liquid water path (LWP) is low during this event and there is little, if any, evidence for supercooled drizzle.

4 Discussion

The synoptic structure differed for each of the three cases examined here, yet all revealed the prevalence of MPCs. Extensive clouds observed during the transit into Davis existed due to the presence of a weak trough, whereas observations made during the two Mawson-based case studies encompassed both the warm and cold sectors of the cyclones. For the two Mawson case studies, the cyclones decayed as they propagated eastward. All events showed the typical three stages of cloud and precipitation observed in cloud systems along the East Antarctic coastline, specifically, (i) pre-precipitation virga falling out of SLW layers at the start of the event, (ii) precipitation reaching the surface (characterised by the strong radar reflectivities) during the event, and finally (iii) post-precipitation

virga in the trailing SLW layers. (Jullien et al., 2020), Multiple layers of SLW cloud were embedded within ice clouds of large vertical extent (i. e. several kilometers deep) for several hours during the central phase of each event (see Figure 3, Figure 9 and Figure 14). This consistent cloud and virga/precipitation structure observed during all three events suggests the ubiquitous occurrence of SLW layers within synoptic-scale cloud systems in the high-latitude austral summer Southern Ocean.

However, small differences in precipitation phase, cloud seeding, and the altitude of the trailing clouds were observed between events. The trailing clouds observed during the events consisted of a single SLW layer in regions of very light wind speeds (< 5 m s^{-1}) either at the top of the boundary layer (Case 2) or as part of a mid-level MPC (Case 1 and Case 3). SLW cloud top temperatures during Case 3 were no warmer than $-31°$C. In all three cases, ice precipitation from the single SLW layer continues for several hours. Ice precipitation was enhanced during Case 2 and Case 3 at Mawson by higher-level seeder ice clouds feeding the SLW layer (Figure 11 and Figure 16), similar to cloud seeding of mid-level SLW layers reported in the tropics (Ansmann et al., 2009), northern mid-latitudes (Herzegh & Hobbs, 1980; Hobbs et al., 1980) and the Arctic (Hobbs & Rangno, 1998).

Generating cells and their associated precipitating ice fall streaks have been extensively documented for extra-tropical Northern Hemisphere cyclones; recent examples include Kumjian et al. (2014); Rosenow et al. (2014); Rauber et al. (2015); Keppas et al. (2018). We summarise our findings for the generating cells observed adjacent to the Antarctic in Table 2. GCs with similar physical characteristics to these Antarctic cases were recently observed over the continental United States (Evans et al., 2005; Rosenow et al., 2014) and the Arctic (McFarquhar et al., 2011). The mean horizontal extent of GCs reported from aircraft observations over the open Southern Ocean is 0.4 km (Y. Wang et al., 2020), lower than the cases adjacent to East Antarctica discussed here. This difference may be due to either a different environment close to the Antarctic (subject to maritime and continental influences), or the limited number of samples discussed here. Our observations of a large range in temperatures of the GCs ($-13°$C to $-30°$C) is consistent with the spread noted elsewhere (Evans et al., 2005; Kumjian et al., 2014).

The GCs reported directly offshore of Antarctica exist in mid-level clouds which are topped by an SLW layer (which is either seen directly by the lidar, or inferred based on large vertical motion and temperature inversion reported by radiosonde), and all ex-

hibited ice precipitation. Air-motion induced oscillations are evident in the GC regions near cloud tops. A region of increasing negative (downward) Doppler velocity is present beneath the GC turbulence region which is likely due to the growth of solid particles in the more quiescent air. This particle growth could be due to riming, which increases the mass to cross-sectional area ratio. Doppler velocities are maximum downward above 1.5 km (the altitude of the lowest SLW layer) for the 26 January event offshore of Davis (Figure 6). The ice particles then sublimate in the very dry air below this lowest SLW layer and Doppler velocities increase near the base of the cloud. This increase is likely due to snow losing cross sectional area and becoming more spherical as the particles become smaller, thereby increasing velocity even as the total condensed mass decreases. The widths of the Doppler spectra near cloud base (or surface) are much larger for the two Mawson cases than the first case. The narrowness of the 26 January event suggests a nearly mono-dispersive snow power spectral density (assuming little to no turbulence or mean motion in the sub cloud region), while the two Mawson cases have much broader spectra. In particular, the Doppler spectra for 1048 UT 15 February is very broad below 0.5 km altitude (Figure 15c). The radiosonde profile from 1130 UT 15 February clearly indicates a well-mixed katabatic layer at these low altitudes which is sufficiently turbulent to alter the Doppler motion of the precipitating ice.

Observations of the multiple SLW layers during Case 1 (Figure 7) and coincident radiosonde profile data indicate that the lowest SLW cloud layer is likely associated with the convective boundary layer while the top SLW layer is likely due to turbulent updrafts. Turbulence driven by cloud-top radiative cooling of the upper SLW layer, in which generating cells are evident (see Figure 6), is likely the main driver of the updrafts (Heymsfield et al., 1991; Hogan et al., 2003), although the strong wind shear within the cloud will also enhance mixing in this layer. In Case 1, a third (middle) SLW layer around 2.3 km is apparent before 19 UT. All three cases featured such embedded (multiple) SLW layers, consistent with the idea that embedded SLW layers within deep ice clouds can be driven by turbulent mixing, and will persist as long as turbulent processes continue (Field et al., 2014). Multiple SLW layers can additionally be maintained via the longwave radiative effect. Cloud-resolving modelling of Arctic multi-layer MPCs indicated that cloud base radiative warming of the upper layer creates a gap in stability between two MPC layers (Luo et al., 2008).

Precipitation out of the base of the SLW layers changed phase in two of the three case studies, in both cases near the end of the event. The supercooled drizzle persisted for about 2 hours in both cases, before changing to predominantly ice precipitation. The LWP during both precipitating drizzle episodes is 50 – 100 g m^{-2}. Non-precipitating SLW clouds in the mid-latitude Southern Ocean generally have LWP < 50 g m^{-2} (Mace & Protat, 2018b). The LWP in the present high-latitude Southern Ocean studies are large enough that drizzle is likely present during the periods identified in Section 3, while supercooled drizzle is either light or not likely present once the LWP dropped well below 50 g m^{-2}. The phase change from supercooled drizzle to ice precipitation was associated with seeding from higher clouds. Supercooled drizzle was present at temperatures between -15°C (cloud base) to -2°C (close to the surface) during these two events. Secondary ice multiplication processes will lead to an increase in ice crystal number concentration within these temperature ranges (Hallett & Mossop, 1974). Given the presence of supercooled drizzle in two out of the three cases presented here, it is likely that this is a common occurrence in cyclonic systems above the Southern Ocean and coastal Antarctic, including within the Hallett-Mossop zone. Supercooled drizzle-sized droplets potentially have important implications for secondary ice production processes over the high-latitude Southern Ocean (Young et al., 2018) as the freezing drizzle is suspected to eject many small droplets, favouring ice multiplication (Korolev et al., 2020).

5 Conclusions

Cloud remote-sensing instruments including W-band radar, a micropulse lidar and a microwave radiometer were mounted aboard an icebreaking vessel *RSV Aurora Australis* during austral summer 2017-18 as it transited the Southern Ocean. We characterise the fine-scale vertical structure and evolution of clouds and precipitation phase present in three systems which passed over the ship when it was between 64°S and 69°S, close or adjacent to the East Antarctic coast.

Multiple layers of SLW were embedded within ice clouds (with cloud tops of 2 – 6 km altitude). The trailing clouds observed in these systems were SLW-topped MPCs, which continued to precipitate ice, either at the top of the boundary layer or at mid-levels. This ice precipitation out of the SLW was enhanced in some cases by seeding from higher-level ice clouds. Ice precipitation is nearly continuous in all but the trailing SLW cloud layer(s) observed as the cyclonic systems are advected away from the ship.

559 Convective generating cells (GCs) were present within mid-level SLW-layer topped
560 MPCs and had physical scales (vertical extents up to 1.0 km and horizontal extent up
561 to 3.6 km) and upward Doppler motions (0.5 – 1.0 m s^{-1}) consistent with observations
562 of GCs made previously at lower latitudes. Supercooled drizzle was observed during two
563 of the three events studied. In both cases the precipitation phase changed from drizzle
564 to predominantly ice following seeding of the drizzling SLW layer by a higher-level ice
565 cloud. The supercooled drizzle events both persisted for around 2 hours, and the driz-
566 zle was present in temperatures as cold as −15°C and as warm as −2°C.

567 Following this characterisation of the fine-scale structure of mixed-phase clouds and
568 precipitation within cyclones adjacent to the Antarctic, the next step is to simulate these
569 events in high-resolution models. Although it is likely that models will have difficulty
570 producing and maintaining SLW, we suspect that by appropriately tuning the microphys-
571 ical schemes using MARCUS observations, we will be able to more accurately reproduce
572 the clouds' vertical structure, evolution and phase partitioning (Vignon et al., 2021).Such
573 a path to model improvement of Southern Ocean clouds could be informed by recent anal-
574 yses of geostationary satellite imagery, which are capable of providing cloud macrophys-
575 ical properties and information on subcloud phase beneath supercooled liquid cloud tops
576 (e. g. Noh et al. (2019)).

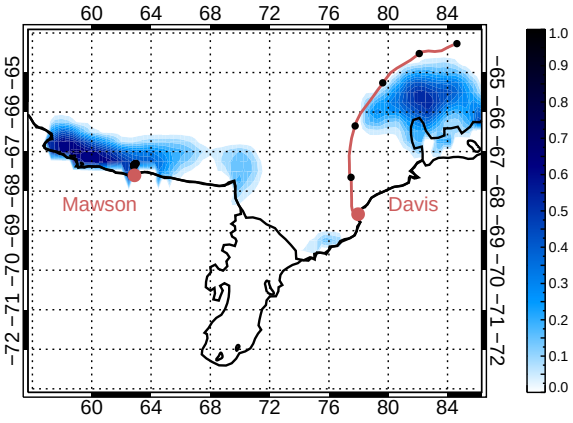

Figure 1. The East Antarctic region of interest. The red line indicates the passage southward into Davis of *RSV Aurora Australis* during Case 1, from 18 UT 25 January until 23 UT 26 January 2018. The small black filled circles indicate the locations of radiosonde launches during the three case studies. The blue contour scale indicates the mean sea ice concentration for February 2018, taken from ERA5 reanalysis.

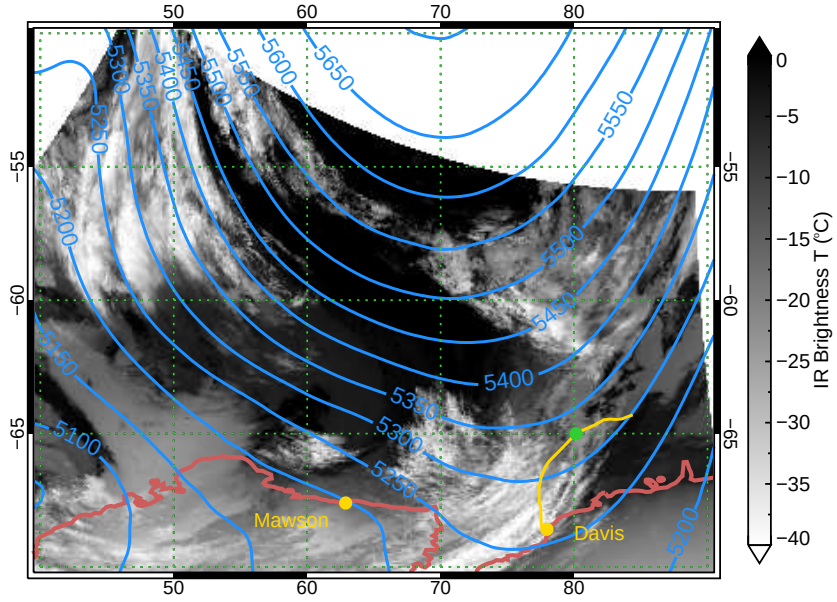

Figure 2. Infra-red brightness temperature (units °C) for the METOP-A overpass at 04 UT 26 January, along with the ERA-5 500 hPa geopotential height at the same time (blue lines, units m). The yellow line indicates the passage southward into Davis of *RSV Aurora Australis* during Case 1, from 18 UT 25 January until 23 UT 26 January 2018, while the green filled circle indicates the ship's location at 04 UT 26 January. Mawson and Davis stations are indicated by the yellow filled circles

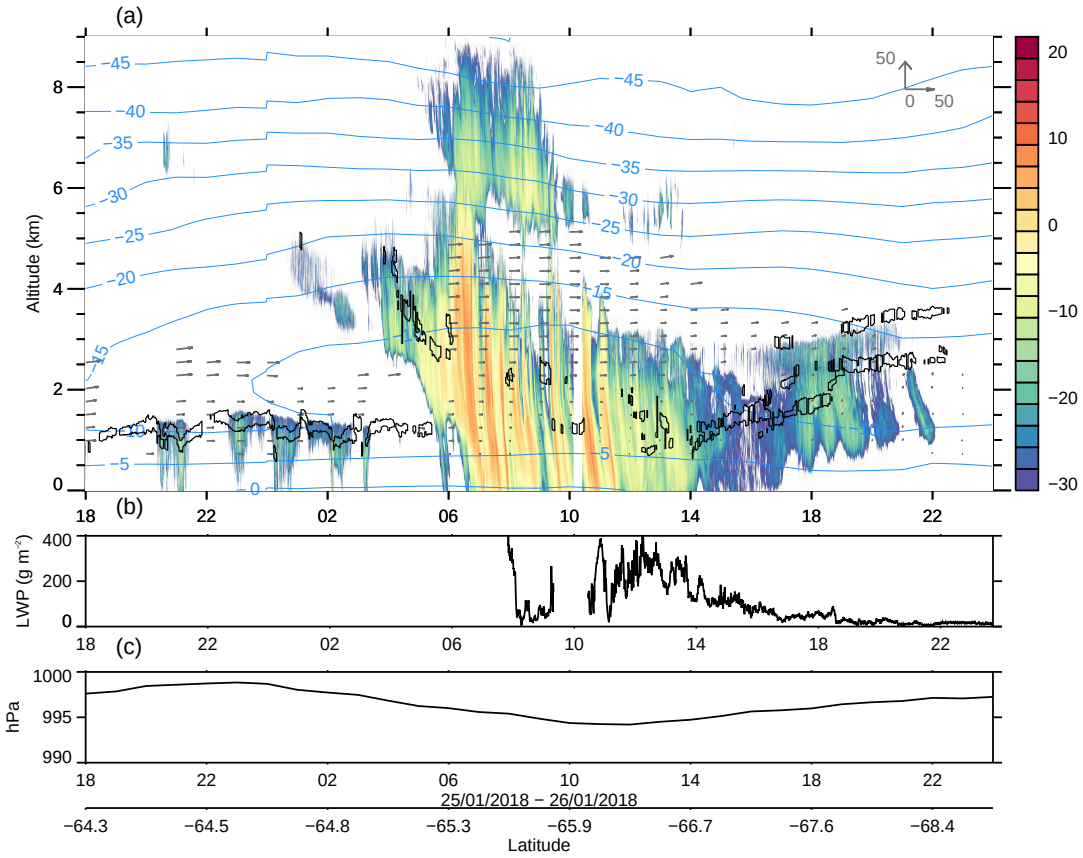

Figure 3. (a) Overview of cloud field and thermodynamic observations made during Case 1. The MWACR reflectivity is shown by the colour (units dBZ). The MPL data are used to determine the location of supercooled liquid water (SLW) clouds (black outlines). The ERA5 temperature field (blue, units of °C) is indicated. A subset of the BSRWP horizontal wind field (grey vectors) are displayed for clarity. Vectors of length 50 m s^{-1} are shown in the top right of panel (a), with the upward arrow indicating the northward direction and the rightward arrow indicating eastward. (b) Liquid water path derived from the MWR: these data were unavailable for the first half of this Case. (c) Surface pressure recorded onboard *RSV Aurora Australis*. The latitude of the observations is given at the bottom.

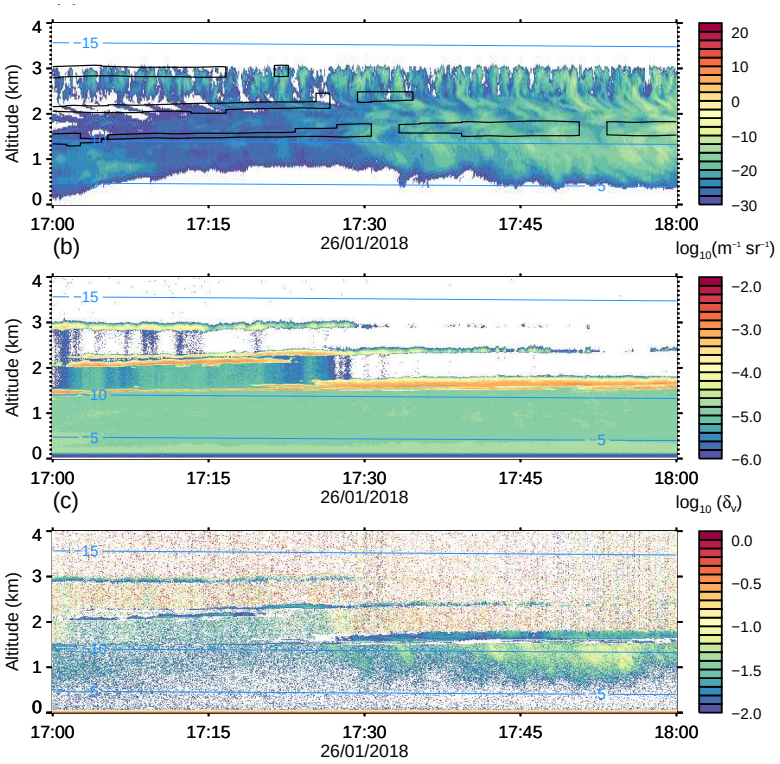

Figure 4. (a) Super-cooled liquid water clouds (black outline) and MWACR reflectivity (colour, units dBZ) between 17 – 18 UT 26 January 2018. (b) The MPL calibrated attenuated backscatter β_{att} and (c) the volume depolarisation ratio δ_v. ERA5 temperatures (units of °C) are indicated by the blue lines on all panels.

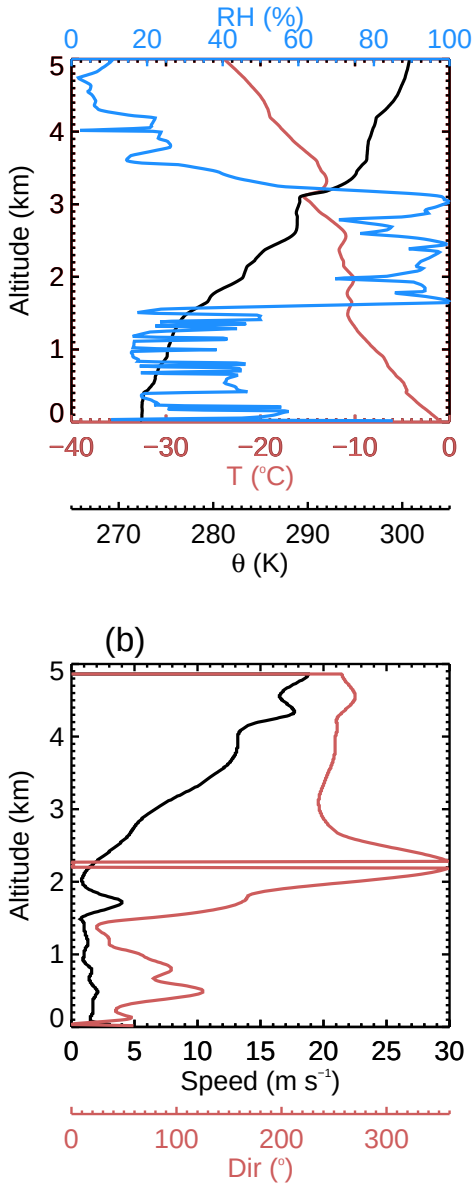

Figure 5. Radiosonde data from the 1732 UT launch on 26 January 2018. (a) Temperature (red), potential temperature (black) and relative humidity with respect to liquid (blue); (b) wind speed (black) and direction which the wind is from (red).

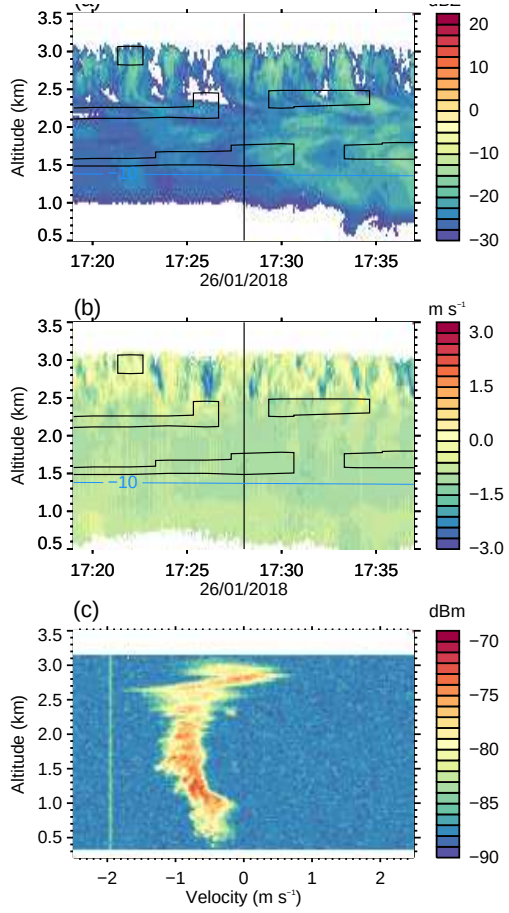

Figure 6. (a) MWACR reflectivity (dBZ) and (b) Doppler velocity (m s^{-1}, positive indicates upward motion) from 1719 - 1737 UT 26 January 2018. (c) The MWACR velocity spectra (dBm) at 1728 UT. The SLW clouds, calculated from two-minute MPL averaged data, are overlain as the black outlines in (a) and (b). The vertical line in (a) and (b) indicates the time of the spectra shown in (c). The ship's location was (67.6°S, 77.4°E) at this time.

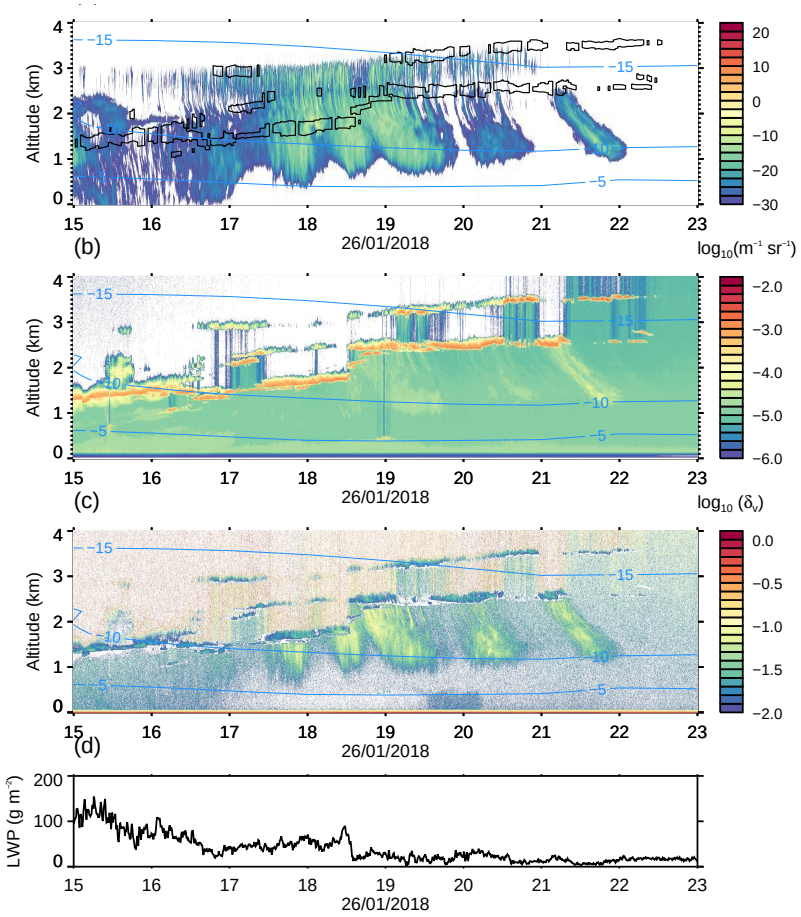

Figure 7. (a) MWACR reflectivity (colour contours, units dBZ) along with the SLW cloud extent determined from the MPL data (black outlines) on 26 January 2018. (b) The MPL calibrated attenuated backscatter β_{att} during the same interval. (c) The volume depolarisation ratio δ_v calculated from the MPL channels. ERA5 temperatures are indicated on all these panels (blue lines, units °C) (d) Liquid water path derived from the MWR.

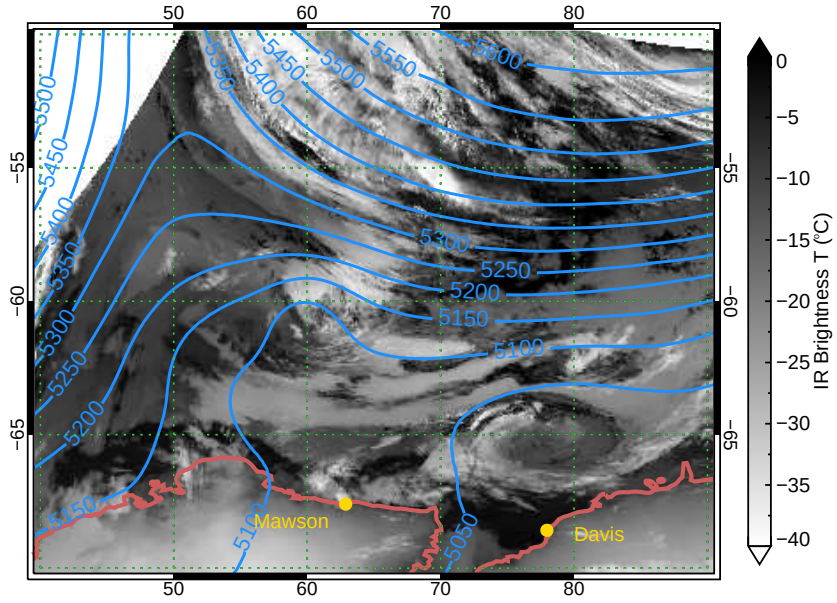

Figure 8. Infra-red brightness temperature (units °C) for the METOP-B overpass at 04 UT 13 February, along with the ERA-5 500 hPa geopotential height at the same time (blue lines, units m). The ship is at Mawson station.

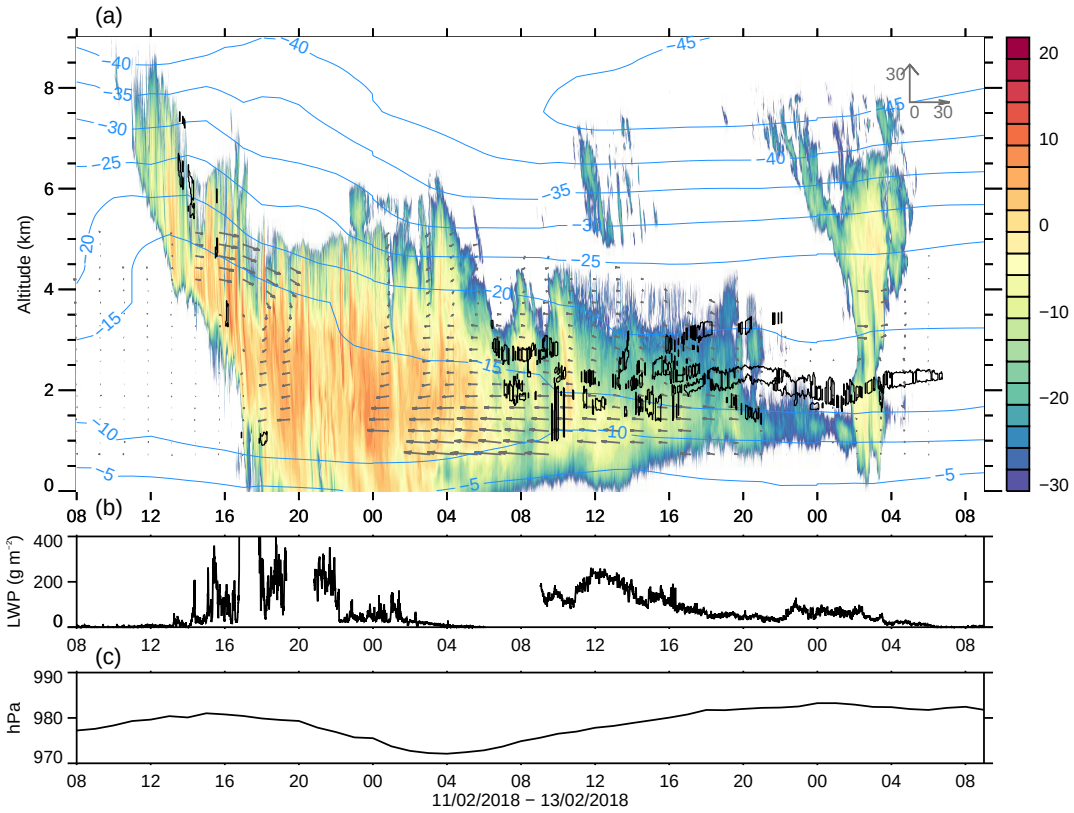

Figure 9. As for Figure 3 except showing the cloud and thermodynamic fields during Case 2, 11 – 13 February 2018, when the ship was at Mawson. Vectors of length 30 m s^{-1} are shown in the top right of panel (a), with the upward arrow indicating the northward direction and the rightward arrow indicating eastward. Data gaps in the MWR LWP and the BSRWP winds are evident.

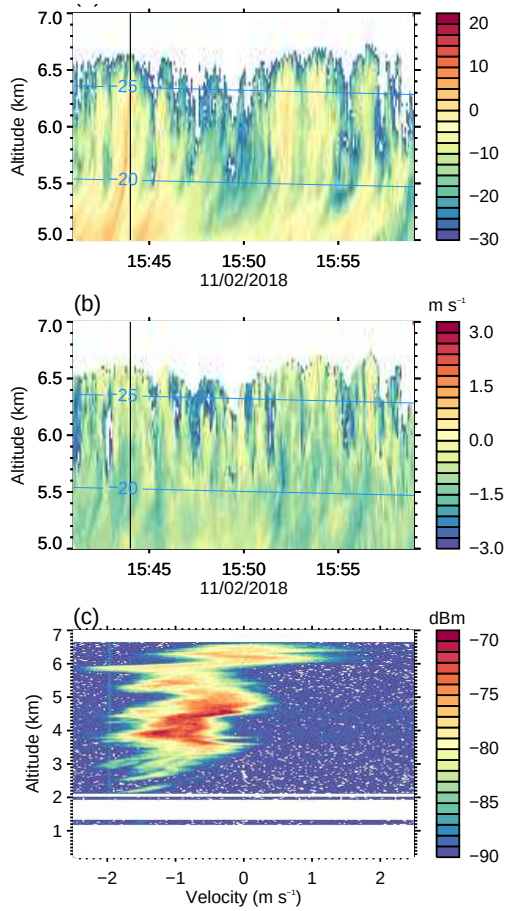

Figure 10. (a) MWACR reflectivity (dBZ) and (b) Doppler velocity (m s^{-1}, positive indicates upward motion) from 1541 – 1559 UT 11 February 2018. (c) The MWACR velocity spectra (dBm) at 1544 UT (note the different y-axis in this panel, from surface to cloud top). The vertical line in (a) and (b) indicates the time of the spectra shown in (c).

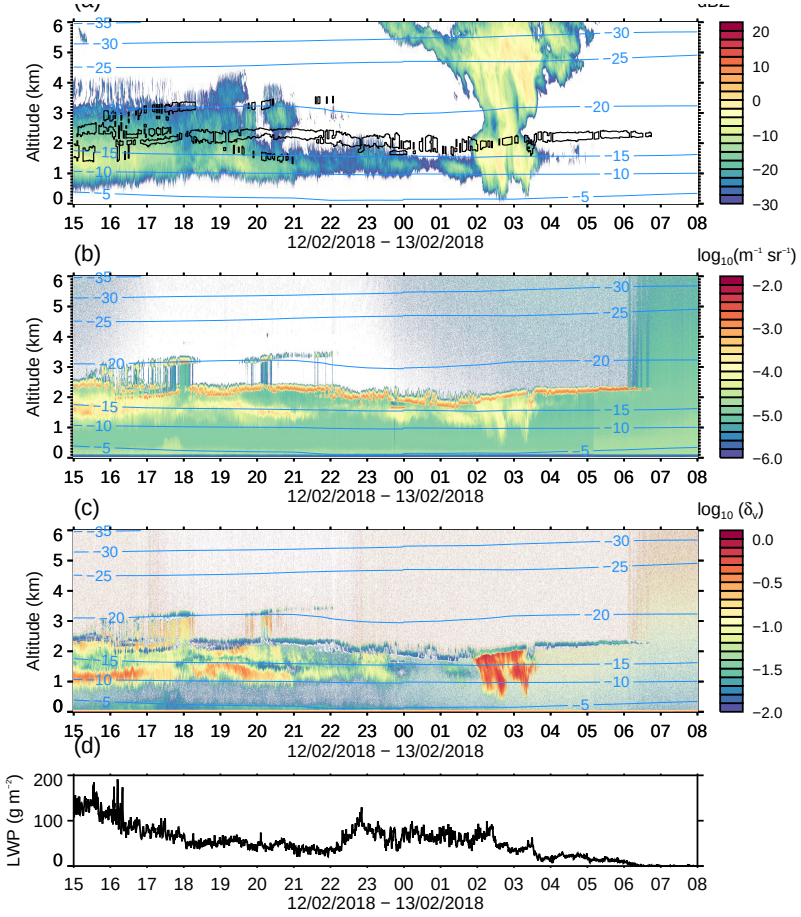

Figure 11. As for Figure 7, except showing the observations between 15 UT 12 February and 08 UT 13 February 2018.

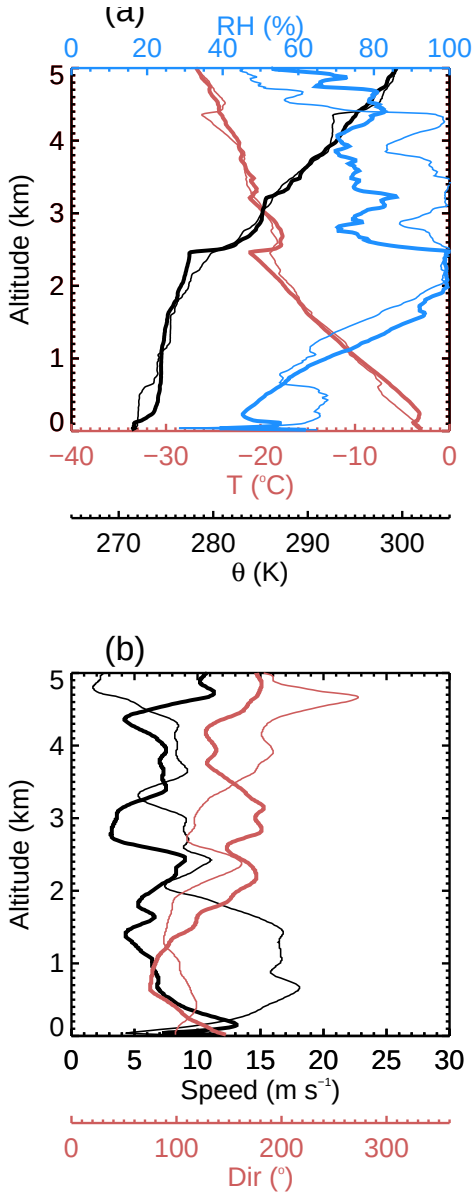

Figure 12. Radiosonde data from the 1730 UT (thin) and 2332 UT (thick) launches on 12 February 2018. (a) Temperature (red), potential temperature (black) and relative humidity with respect to liquid (blue); (b) wind speed (black) and direction which the wind is from (red).

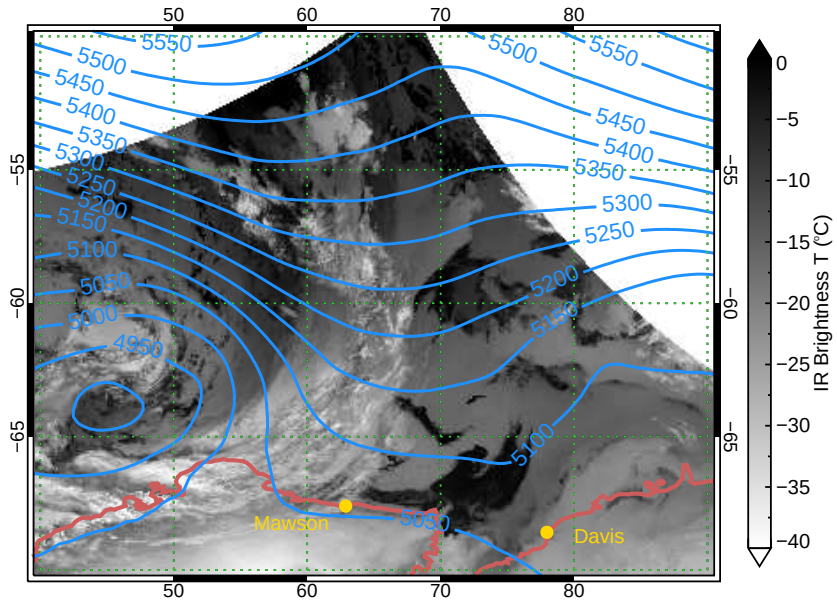

Figure 13. Infra-red brightness temperature (units °C) for the METOP-B overpass at 19 UT 14 February, along with the ERA-5 500 hPa geopotential height at the same time (blue lines, units m). The ship is at Mawson station

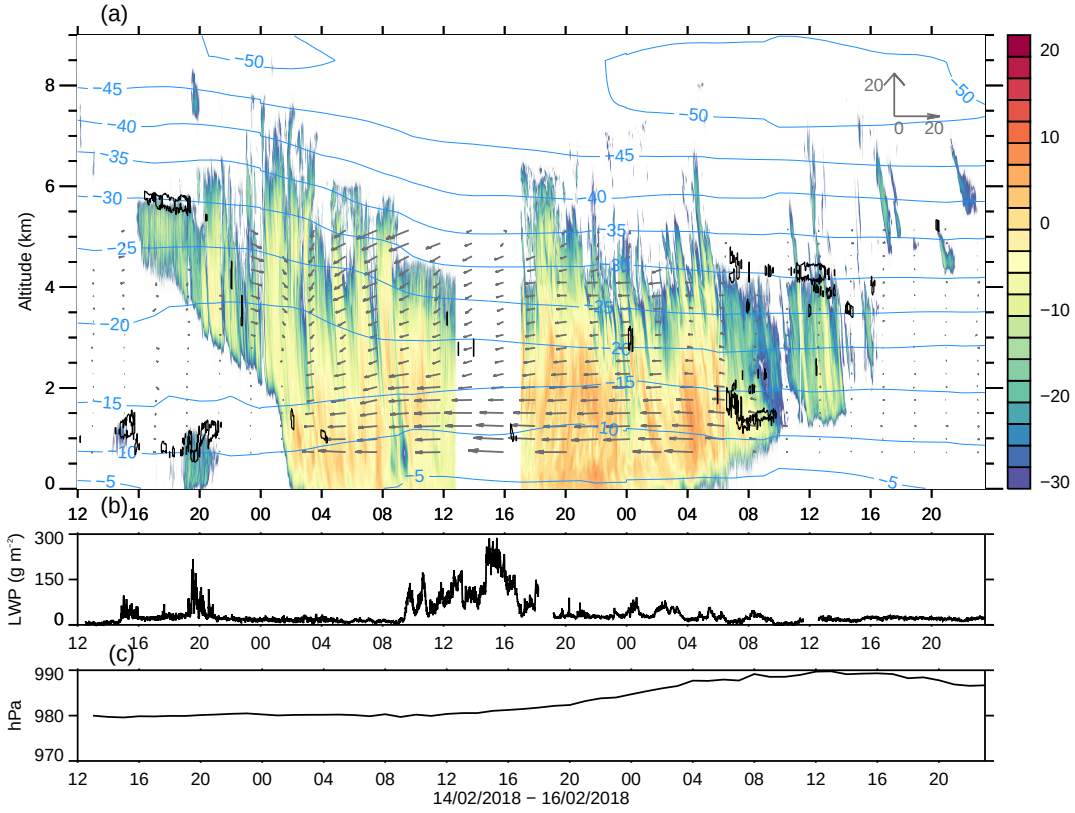

Figure 14. As for Figure 3 except showing the cloud and thermodynamic fields during Case 3, 14 – 16 February 2018, when the ship was at Mawson. Vectors of length 20 m s^{-1} are shown in the top right of panel (a), with the upward arrow indicating the northward direction and the rightward arrow indicating eastward. The MWACR cloud radar was not operational between 13 - 17 UT, 15 February.

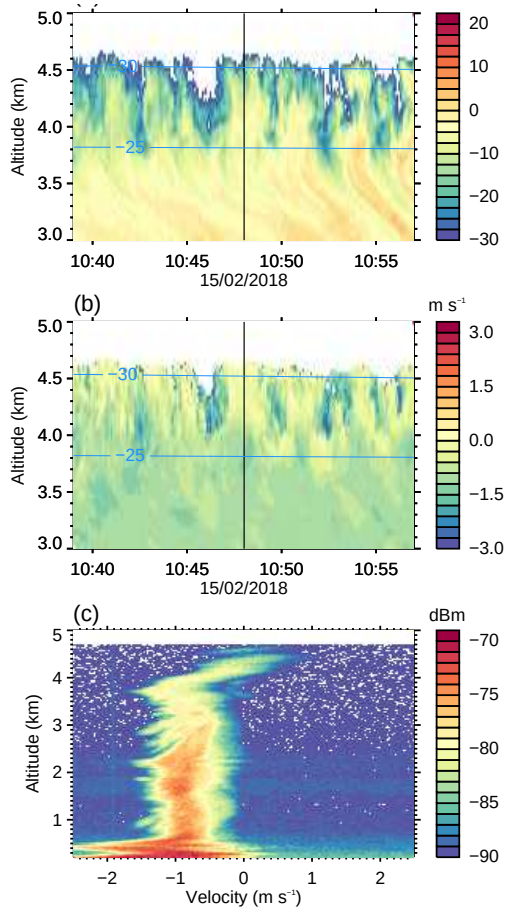

Figure 15. (a) MWACR reflectivity (dBZ) and (b) Doppler velocity (m s^{-1}, positive indicates upward motion) from 1039 – 1057 UT 15 February 2018. (c) The MWACR velocity spectra (dBm) at 1048 UT (note the different y-axis in this panel, from surface to cloud top). The vertical line in (a) and (b) indicates the time of the spectra shown in (c).

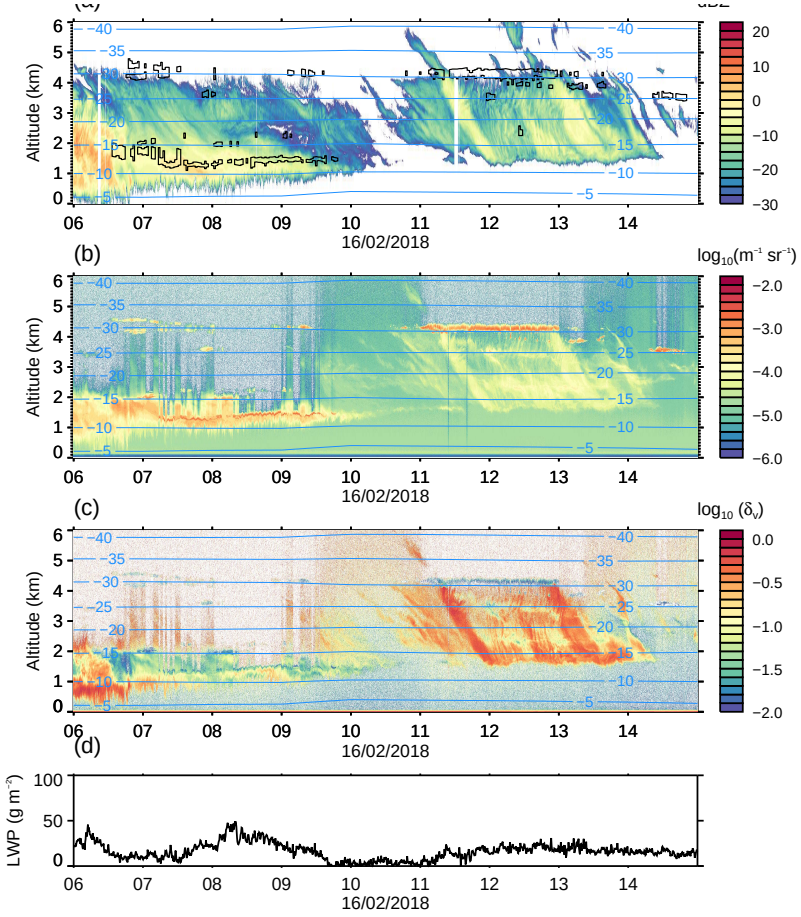

Figure 16. As for Figure 7, except showing the observations between 06 UT and 15 UT 16 February 2018.

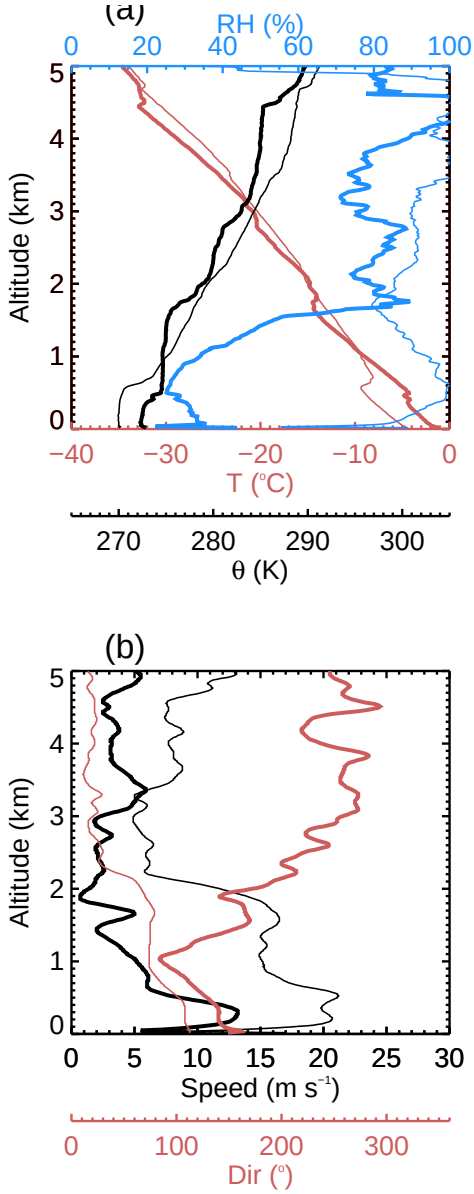

Figure 17. Radiosonde data from the 1130 UT 15 February (thin) and 1130 UT 16 February (thick) launches. (a) Temperature (red), potential temperature (black) and relative humidity with respect to liquid (blue); (b) wind speed (black) and direction which the wind is from (red).

Table 1. MARCUS instrumentation and their data used in the present study.

Instrument	Observed or derived parameters used
Marine W-band Cloud Radar (MWACR)	Reflectivity, Doppler velocity
Micro-pulse lidar (MPL)	Backscatter, depolarisation ratio, cloud extent, cloud phase
Radiosondes	Temperature, humidity, wind velocities
Backscatter radar wind profiler (BSRWP)	Horizontal wind velocities
2-channel microwave radiometer (MWR)	Liquid water path, precipitable water vapor

Table 2. Physical characteristics of generating cells observed adjacent to Antarctica. The temperature T, from ERA5, given below is that at cloud top height. Horizontal extent of the GCs are calculated using the radiosonde-derived wind speeds and directions, and the ship motion, as described in Section 3. The Doppler velocities given here are not corrected for the ship's negligible heave velocities (see text for details).

Case	Date	T	Horizontal extent	Vertical extent	Maximum upward Doppler velocity
1	26 January	−13°C	1.2 km	0.7 – 0.8 km	1.0 m s^{-1}
2	11 February	−26°C	2.4 – 3.6 km	1.0 km	1.0 m s^{-1}
3	15 February	−30°C	0.6 – 1.8 km	0.9 km	0.5 m s^{-1}

Acknowledgments

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`data.aad.gov.au`. The MPL calibrated backscatter and derived cloud phase products, along with the LWP and IWC from the MWR are permanently archived at `https://data.aad.gov.au/metadata/records/AAS_4292_MARCUS_Case_Studies` (Alexander, 2020). All data are freely available following registration. The contribution of GM was supported by DoE BER award DE-SC0018626. The Bureau of Meteorology's contribution to this study was partly funded by the National Environmental Science Program (NESP), Australia, and the Australian Antarctic Program Partnership (AAPP). We thank two anonymous reviewers whose insightful comments helped improve an earlier version of this manuscript.

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