A characterization of clouds and precipitation over the Southern Ocean from synoptic to micro scales during the CAPRICORN field campaigns

Estefania Montoya Duque[1], Yi HUANG[2], Steven Siems[3], Peter May[4], Alain Protat[5], and Greg McFarquhar[6]

[1]University of Melbourne
[2]The University of Melbourne
[3]MONASH UNIVERSITY
[4]Monash University
[5]Australian Bureau of Meteorology
[6]Cooperative Institutes for Mesoscale Meteorological Studies

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Abstract

The persistent Southern Ocean (SO) shortwave radiation biases in climate models and reanalyses have been associated with the poor representation of clouds, precipitation, aerosols, the atmospheric boundary layer, and their intrinsic interactions. Capitalizing on shipborne observations collected during the Clouds Aerosols Precipitation Radiation and atmospheric Composition Over the Southern Ocean (CAPRICORN) 2016 and 2018 field campaigns, this research investigates and characterizes cloud and precipitation processes from synoptic to micro scales. Distinct cloud and precipitation regimes are found to correspond to the seven thermodynamic clusters established using a K-means clustering technique, while less distinctions are evident using the cyclone and (cold) front compositing methods. Cloud radar and disdrometer data reveal that light precipitation is common over the SO with higher intensities associated with cyclonic and warm frontal regions. While multiple microphysical processes and properties are present in several cloud regimes, ice aggregation appears to be dominant in deep precipitating clouds. Mixed phase, and in some cases, riming was detected in shallow convective clouds away from the frontal conditions. Two unique clusters with contrasting cloud and precipitation properties are observed over the high-latitude SO and coastal Antarctica, suggesting distinct physical processes therein. Through a single case study, in-situ and remote-sensing data collected by an overflight of the Southern Ocean Clouds Radiation Aerosol Transport Experimental Study (SOCRATES) were also evaluated and complement the ship-based analysis.

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E. Montoya Duque[1,2], Y. Huang[1,2], S.T. Siems[2,3], P.T. May[3], A. Protat[4], G. M. McFarquhar[5,6]

[1]The University of Melbourne, Melbourne, Australia
[2]Australian Research Council Centre of Excellence for Climate Extremes, Melbourne, Australia
[3]Monash University, Melbourne, Australia
[4]Australian Bureau of Meteorology, Melbourne,Australia
[5]Cooperative Institute for Severe and High Impact Weather Research and Operations (CIWRO)
[6]School of Meteorology, University of Oklahoma, Norman, OK, USA

Key Points:

- Distinct cloud and precipitation regimes correspond to the diverse Southern Ocean synoptics, defined using a K-means clustering technique
- Evidence shows multiple microphysical features,like mixed phase in shallow convection and ice aggregation in deep precipitating clouds
- Two unique clusters with contrasting cloud and precipitation properties are over the high-latitude region, where models have large biases

Corresponding author: Estefania Montoya Duque, emontoyaduqu@student.unimelb.edu.au

Abstract

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Plain Language Summary

The current generation of climate models and reanalyses products have difficulties in properly representing the radiative balance over the Southern Ocean (SO), which can be traced to the poor understanding of clouds and precipitation processes in this region. The remote location of the SO is a key factor for the lack of field observations that allow the scientific community to address the above-mentioned problem. However, recent coordinated field campaigns have collected an unprecedented amount of data, offering new opportunities to explore this understudied region. This research paper aims to study clouds and precipitation processes over the SO using shipborne data collected from two field campaigns in 2016 and 2018. Using different synoptic classification techniques, we identify unique macro and micro cloud and precipitation behaviors that correspond to the various weather patterns across a wide range of latitudes. In addition, we use aircraft observations collected from an overflight to evaluate and complement our analysis of the shipborne data. The study offers a framework that may help better understand the nature of the model biases over the SO.

1 Introduction

The Southern Ocean (SO) is a region of significant interest for its capacity to store excess heat and carbon. Yet large shortwave radiative biases over the SO continue to exist in both climate models and reanalysis products, which are primarily attributed to the poor representation of clouds, precipitation, aerosols, and their interactions in this region (Bodas-Salcedo et al., 2012, 2014; Kay et al., 2016; Zelinka et al., 2020; McFarquhar et al., 2021). These errors limit the ability of models to predict climate in this region, and the associated global climate feedbacks (Bodas-Salcedo et al., 2014; Ceppi et al., 2016; Gettelman et al., 2019).

While many studies have found that an incorrect ice-liquid partitioning, typically in the cold sector of extratropical cyclones (Bodas-Salcedo et al., 2012; Williams et al., 2013; Bodas-Salcedo et al., 2014; Naud et al., 2014), constitutes a leading cause of the model biases, mechanisms that are responsible for these deficiencies are not yet clear. In addition, compensating errors associated with multi-layer clouds (Protat et al., 2017), biases in the frontal region of extratropical cyclones (Kelleher & Grise, 2019), as well as errors in shallow cyclones near the Antarctic continent (Mason et al., 2015) have all been documented. These findings underline the complicated nature of the models biases and the dynamical and physical processes at play.

The challenges in understanding and modeling the SO climate has helped motivate a number of recent international field campaigns with the aim to improve the fundamental understanding of key atmospheric processes in this region through coordinated aircraft, shipborne and ground-based observations. Among these efforts, four recent collaborative field campaigns funded by agencies in the United States and Australia are summarized in McFarquhar et al. (2021). These projects include i) The Clouds Aerosols Precipitation Radiation and atmospheric Composition Over the Southern Ocean (CAPRICORN), 2016 and 2018; ii) The Macquarie Island Cloud Radiation Experiment (MICRE), 2016-2018; iii) The Measurements of Aerosol, Radiation, and Clouds over the Southern Ocean (MARCUS), 2017-2018; iv) The Southern Ocean Cloud Radiation and Aerosol Transport Experimental Study (SOCRATES), 2018.

The comprehensive measurements collected from these projects are being utilized to examine clouds, aerosols, precipitation and radiation characteristics over the SO in unprecedented detail. Using remote-sensing and in-situ observations, recent studies have refined our understanding of the bulk statistics of cloud occurrence and phase partitioning (Mace & Protat, 2018a), properties of non-precipitating liquid-phase low-level clouds (e.g. Mace and Protat (2018b), Mace et al. (2021)), as well as cloud properties in the cold sector of extratropical cyclones (e.g. Y. Wang et al. (2020), D'Alessandro et al. (2021), Zaremba et al. (2020)). Case studies have also been carried out to examine special phenomena such as an atmospheric river (Finlon et al., 2020), mesoscale cellular convection (Lang et al., 2021), and convective generating cells near the cloud tops (Alexander et al., 2021; Y. Wang et al., 2020). These new observations have also enabled the evaluation of model simulations across a range of spatial and temporal scales (e.g. Protat et al. (2017), Atlas et al. (2020), Zhou et al. (2020), Gettelman et al. (2020)).

Despite the significant advancements, many key questions remain unaddressed. One under-studied area is the understanding of processes involved in the life cycle of precipitation. Previous studies using precipitation records from Macquarie Island have identified the prevalence of drizzle and light precipitation and linked their bulk statistics to frontal and cyclonic activities (Z. Wang et al., 2015; Lang et al., 2018). More broadly, however, precipitation properties across the SO are largely unknown. Model errors in precipitation processes, such as the long-standing "warm-rain" process errors, remain widespread in the latest generation of climate models, which bias cloud feedbacks by as much as the CMIP5-to-CMIP6 climate sensitivity difference (Mülmenstädt et al., 2021).

Moreover, fewer studies have thus far focused on understanding the thermodynamic structure of the lower troposphere and how it controls the cloud-precipitation properties and processes over the SO, within the context of synoptic meteorology. Understanding these relationships is of importance, as the thermodynamics is arguably the largest term in water budget between different cloud types (McCoy et al., 2021). It is beneficial to explore these relationships at shorter timescales, given the transient nature of the weather systems that dominate the mid- and high-latitudes (Kelleher & Grise, 2019). Such practice is also a necessary step towards developing a physical, process-level understanding that is required for constraining the cloud-precipitation processes while mitigating compensating process errors in climate models (Mülmenstädt et al., 2021).

Using the collection of 2186 atmospheric soundings from the above-mentioned field campaigns, a recent study by Truong et al. (2020) was among the first to examine the relationships between the synoptic meteorology and lower tropospheric thermodynamic structure over the SO, using a K-means clustering complemented by front and cyclone composite analyses. The authors identified seven distinct clusters, which uniquely represent the various thermodynamic conditions over the SO, extending the knowledge derived from a 16-year record of soundings from Macquarie Island, where the mid-latitude storm track clusters dominate (Lang et al., 2018).

Built upon the analysis in Truong et al. (2020), the aim of this study is to examine cloud-precipitation properties and processes within the context of thermodynamic clusters as well as front and cyclone composites, using the shipborne observations collected from CAPRICORN experiments. In particular, we seek to address two questions: (1) Are there distinct cloud regimes that correspond to the unique thermodynamic and synoptic conditions? (2) How do the microphysics and precipitation processes differ in the various cloud regimes and atmospheric environments? We also present a case study, where we combine remote-sensing and in-situ observations from CAPRICORN and SOCRATES during a short overflight to provide further insights into the interplay between multiple processes. The description of the data and methods is presented in Section 2. Results are in Sections 3 and 4. Finally, the discussion and conclusions are in Section 5.

2 Data and Methods

2.1 Field Campaigns

The CAPRICORN field campaign was conducted with the RV Investigator, operated by the Australian Marine National Facility, consisting of two voyages led by the Australian Bureau of Meteorology (BoM). The first voyage (CAPRICORN I) was carried out from 13 March to 15 April 2016, traversing in the Australian water between Hobart, Australia (42.8^{o}S, 147.3^{o}E) and around 55^{o}S. CAPRICORN II was executed in austral summer (from 11 January to 21 February 2018) and had a broader latitudinal coverage (from Hobart to around 64^{o}S). As the ship track was primarily designed to meet oceanographic objectives, the RV Investigator sometimes remained at the same station for 6-24 hours, commonly at high latitudes poleward of the oceanic polar front. Together these two voyages produce a rich dataset encompassing clouds, aerosols, precipitation and radiation measurements over the Australian sector of the SO (McFarquhar et al., 2021).

The Southern Ocean Cloud Radiation and Aerosol Transport Experimental Study (SOCRATES) campaign undertook 15 research flights from Hobart to near 62°S (134-163°E) during January-February of 2018 (Y. Wang et al., 2020). The flights were undertaken with the NSF/NCAR HIAPER Gulfstream V (GV) aircraft, making in-situ and airborne remote-sensing measurements of cloud, aerosol, and planetary boundary layer (PBL) properties, including (but not limited to) the structures and vertical distributions of liquid and mixed-phase clouds and aerosols. The flights were designed to sample the cold sectors of extratropical cyclones, where many climate models have the largest radiation biases (Marchand et al., 2014; McFarquhar et al., 2021).

2.2 Remote sensing data

Both the RV Investigator and the GV HIAPER included Doppler cloud radar (see Table 1), allowing for an opportunity to obtain synchronous cloud radar data during overflight periods. As has been established in the literature (e.g. Bodas-Salcedo et al. (2011), Huang et al. (2015)), a cloud radar detects different types of ice and water particles. For an in-cloud temperature less than 0^{o}C, reflectivities larger than 5 dBZ commonly indicate a cloud dominated by large ice particles. 5 dBZ or less usually indicate Super-cooled Liquid Water (SLW) and/or small ice particles (including their coexistence). Instead, for temperatures greater than 0^{o}C, liquid non-precipitating clouds are typically represented by a reflectivity lower than -15 dBZ, drizzle by radar reflectivities between -15 and -7.5 dBZ; precipitating clouds by a reflectivity larger than -7.5 dBZ. The cloud radar from the CAPRICORN field campaigns also measured Doppler velocity, which is a combination of falling particles' speed and vertical wind speed. Different ice habits have distinct falling speeds, making it difficult to identify the type of ice. Nevertheless, we can deduce the likely presence of certain ice forming mechanism by the reflectivity, Doppler velocity, and temperature range.

Table 1. Remote sensors and in-situ instruments deployed on the RV Investigator and GV (HIAPER) aircraft during the CAPRICORN and SOCRATES field campaigns.

Instrument Name	Description	Measurement Ranges	Key Variables
	Remote sensors/CAPRICORN		
Cloud radar BASTA[1*] Delanoë et al. (2016), UCAR/NCAR EOL (2018)	W-band cloud radar 94.95 GHz. Mounted on a stabilized platform to endure vertical radar points.	Temporal resolution 12 s and four vertical resolutions (12.5, 25, 100, 200 m). Minimum valid signal distance 40 m, maximum observable altitude 12 km minimum detectable radar reflectivity -45 dBZ at 1 km. Time: 1 min	Reflectivity, Doppler velocity.
	In-situ/CAPRICORN		
ODM470 Disdrometer Klepp et al. (2018)	OceanRAIN[2*] dataset. Emits a light from a diode at 880 nm and measure a volume of 120 nm in diameter. 1 minute resolution. 128 bins with logarithmic increase from 0.1 to 20 nm in diameter.	Very light (001-0.09 mm/hr), light (0.1-0.99 mm/hr), moderate (1-9.99 mm/hr), intense (10-49.99 mm/hr), extreme (above 50 mm/hr)	Precipitation rate, intensity, and phase.
	Remote Sensors/SOCRATES		
Cloud radar HIAPER HCR[3*] Vivekanandan et al. (2015) UCAR/NCAR - EOL (2014) NCAR/EOL (2023)	W-band cloud radar 94.4 GHz.	Resolution 30-150 m, sensitivity of -39.6 dBZ at 1 km, radial velocity uncertainty 0.2 m s^{-1} at a vertical velocity of 2 m s^{-1}. Time: 0.5 s (corresponding to a spatial resolution of 83-105m.	Reflectivity, Doppler velocity
	In-situ cloud probes/SOCRATES		
Two-Dimensional Cloud Probe (2DC) Wu and McFarquhar (2016)	Cloud optical array imaging probe with 64 photodiodes, a 25 μm resolution. Sample volume is a function of Diameter (D)	D: > 200 μm IWC: derived following Baker and Lawson (2006)	IWC, Nice, Dmm[4*], cloud particle images
Cloud Droplet Probe (CDP) Lance et al. (2010)	Forward scattering probe that sizes particles using the Mie Theory. It emits a light from a laser beam and measures droplets (no ice)	Diameter: 2–50 μm	LWC, Nc
Particle Habit Imaging and Polar Scattering Probe (PHIPS HALO) Abdelmonem et al. (2016), Schnaiter et al. (2018), Järvinen et al. (2022, Under Review)	Two stereo microscopic cameras and detectors for measuring the scattering of light	Detecting particles from 20 to 700 μm of diameter (for ice, the lower diameter range is 50 μm)	Particle images, multi-angular scattering
Rosemount Icing Detector (RICE) Baumgardner and Rodi (1989)	Piezoelectric sensor which detects presence of SLW.	Minimum SLW detected is 2 mVm^{-1} McFarquhar et al. (2013)	Voltage change
	State parameters/SOCRATES		
Vertical Cavity Surface Emitting Laser Hygrometer (VCSEL) Diao, M. (2018)	Lase based hygrometer.	Water Vapor concentrations	Relative Humidity

1∗ BASTA (Bistatic Radar System for Atmospheric Studies).

2∗ OceanRAIN (Ocean Rainfall And Ice-phase precipitation measurement Network).

3∗ HIAPER (High-Performance Instrumented Airborne Platform for Environmental Research).

4∗ Liquid Water Content (LWC), Ice Water Content (IWC), particle number concentration (Nc), Ice number concentration (Nice), median mass diameter (Dmm). Super-Cooled Liquid Water (SLW), particle size (D).

2.3 In-situ data

To measure surface precipitation, the RV Investigator employed an ODM470 disdrometer, which is part of the OceanRAIN dataset (Ocean Rainfall And Ice-phase precipitation measurement Network, Klepp et al. (2018)), see table 1. Values below 0.01 mm/hr and spurious data are set to zero (refer to Klepp et al. (2018) for details on the intensity labeling). Note that the thermodynamic phase has inherent uncertainties in the estimated precipitation rates for mixed and snow phase precipitation (Klepp et al., 2018). Our initial analysis has identified two precipitation events with a 1-minute precipitation rate apparently exceeding 100 mm/hr (2018-01-27 22:00 to 23:13 UTC, and 2018-02-09 around 10:50 UTC). While these events have been classified as extreme, the actual precipitation rates are subject to very large uncertainties and are likely affected by the presence of ice and so should be treated with caution. All values above 101 mm/hr (99.85% percentile which represent 0.021% of the total data) are excluded in the present analysis. The threshold is selected based on the inspection of the disdrometer time series and cross-examination of the C-band radar during those times.

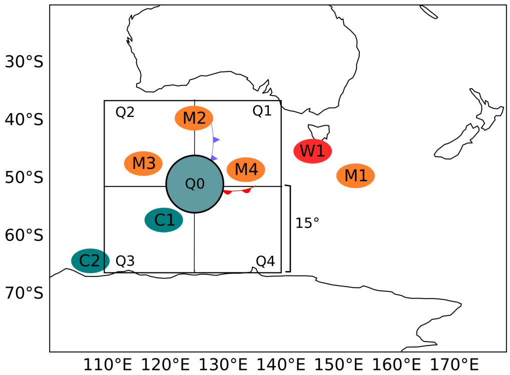
A number of in-situ cloud microphysics datasets from the SOCRATES field campaign (Table 1) are also analyzed for a case study during one overflight transect above the RV Investigator (Section 3.4) (UCAR/NCAR EOL, 2019; Wu & McFarquhar, 2019; Schnaiter, 2018). Detailed information on the processing of in-situ cloud probe data and an overview of the uncertainties of the derived products and cloud parameters are provided in Y. Wang et al. (2020), McFarquhar et al. (2021), D'Alessandro et al. (2021), Baumgardner et al. (2017), and McFarquhar et al. (2017). It is worth highlighting that the 2DC is used in this analysis even though McFarquhar et al. (2021) stated that the use of the 2DS (which measures particles with similar sizes) was preferential because the 2DC suffered frequent fogging issues during SOCRATES. However, for the time period analyzed, the 2DS was suffering from technical issues. A careful inspection of the 2DC images for the analyzed period did not show any evidence of degraded image quality. For other time periods without degraded 2DC image quality and available 2DS data, Schima et al. (2022, In Preparation) showed that the 2DC had a slight underestimation of Nc by a factor varying between 0.5 and 0.75 (e.g., for flight on 4 February 2018). Corrections for out of focus particles, and shattered particles are made following techniques referenced above and incorporated into the University of Illinois/Oklahoma Optical Array Probe Processing Software (UIOOPS, McFarquhar et al. (2018)).

2.4 Synoptic and thermodynamic conditions

In this study, we characterize clouds and precipitation under various atmospheric conditions using three different, but complementary methods: clusters, cyclone composites and cold front composites. First, is the seven thermodynamic clusters defined in Truong et al. (2020) which are found to be able to represent the mid-latitude storm track region (M1-M4), cyclones over the high-latitude SO (C1) and the sub-Antarctic (coastal) waters (C2) (Figure 1). We also use traditional synoptic classifications for constructing composites: cyclone and frontal activity detection. Extratropical cyclones are detected with the University of Melbourne (UM) cyclone detecting and tracking scheme using the 3-hourly ERA5 reanalysis product at a 0.25^o spatial resolution (Murray & Simmonds, 1991). The UM cyclone tracking and detecting method is a well-established global method for cyclone detection (Pepler et al., 2020). For a given cyclone, we define four quadrants as in Lang et al. (2018) (Q1-Q4; within a distance up to 15^o from the cyclone center) and one center (Q0; representing all soundings within 5^o distance of the cyclone center). Fronts are detected using the method of Berry et al. (2011) with hourly ERA5 reanalysis at a 0.75^o spatial resolution. Only cold fronts within 15^o from the RV Investigator are considered. The cold Frontal sections are defined as distances within 2.5^o of the front line, whereas the pre-frontal (post-frontal) sections are between -15 and -2.5^o (2.5 and 15^o).

A schematic diagram that describes the general relationships between the various classifications are presented in Figure 1.

It is worth noting that the weather conditions over the SO are highly variable. Thus, the location of warm and cold fronts relative to the cyclone center can differ significantly from the classic diagram shown in Figure 1. Also, the spatial and temporal resolution of ERA5 used for the cyclone and front detection can induce uncertainties in their exact positions. Nevertheless, the seven clusters extend beyond the common storm-track weather patterns typically represented in the cyclone and front composites.



Cluster	Characteristics
W1	Characterised by warm air advection from the Australian continent in pre-frontal regions north of ocean polar front
M1	Typically found in high-pressure systems (and ridging) in large scale subsidence
M2	Located at the north-northeast of the cyclone centre close to cold fronts but removed from the cyclone centre
M3	Represents the post-frontal area of a cold front, and northwest of the cyclone centre
M4	A warm front cluster
C1	Represents the conditions poleward of the ocean polar front near cyclones
C2	Indicates the conditions in the coastal Antarctica area, it can be located southwest of the cyclone centre

Figure 1. A conceptual illustration of the seven thermodynamic clusters and their relationships to the extratropical cyclone, cold and warm front, derived in Truong et al. (2020). The red circle indicates the warm cluster (W1), Orange circles the medium clusters (M1-M4), and dark blue circles the cold clusters (C1-C2) and the proximity to Q0. Q0 represents the cyclone center, Q1-Q4 indicate the four cyclone quadrants. The red (blue) curve with half-circles (triangles) indicates the warm (cold) front. Note that cold and warm fronts are not always within the above illustrated quadrants. On the right, main cluster characteristics are also presented.

Of the 2186 soundings employed in Truong et al. (2020), 266 were from CAPRICORN 2016 and 2018. To analyze the clouds and precipitation associated with each of these sounding profiles and the corresponding cluster, cyclone and front, data are taken within ±1.5 hours of each sounding's launch time (see Table 2 for the number of sounding per classification). The length of the time window was chosen to ensure that the ship traveled less than 1 degree, yet provided enough samples for a robust statistical analysis. Time windows from ± 0.5 to 4.0 hours were tested, but did not qualitatively change the results.

3 Cloud and precipitation properties

To provide insights into the thermodynamic phase and microphysical processes of the observed clouds and precipitation, Contoured Frequency by Altitude Diagram (CFAD, Yuter and Houze (1995)) and a variant, Contour Frequency by Temperature Diagram (CFTD, Huang et al. (2015)) are constructed from the RV Investigator cloud radar reflectivity for the various synoptic classifications. These diagrams do not assume prior statistics, so they can be used for non-Gaussian and multi-modal distributions such as radar data since they preserve the information in the frequency distribution (Yuter & Houze, 1995). Additionally, we consider the median radar reflectivity as a function of the Doppler velocity and temperature (altitude) (Figures 2, 3 and 4). We note that the CFTD is able to clearly define the melting level, which may be of particular interest. The cloud mask product from the CAPRICORN cloud radar and lidar information (Huang et al., 2019) is used to estimate cloud cover percentage, which is defined as the ratio between the time when cloud was observed over the ship and the total length of the time-window for a given synoptic condition.

The received power by the cloud radar is affected by the particle size observed such that the radar is sensitive to large particles. As such the composite structures of the radar reflectivity and Doppler velocity can be examined jointly to infer plausible dominant ice growth processes, when the known limitations of a single-frequency cloud radar are properly taken into account. For instance, given the low density and large size of ice aggregates compared to liquid drops, aggregation is likely dominant when the reflectivity in the temperature range (-30 to -15^{o}C) increases more uniformly towards lower altitudes (higher temperatures), while the Doppler velocity remains relatively small (between 0 and -1 ms^{-1}, Thompson et al. (2008)) yet exhibiting a similar tendency. On the other hand, strong riming may be present when moderate-to-strong reflectivities are accompanied by higher fall velocities, particularly at the sub-freezing temperature range in a convective environment where supersaturation with respect to liquid water is more easily achieved.

We consider both surface and in-cloud precipitation. The shipborne disdrometer records are used to determine the 1-minute surface precipitation rates and the thermodynamic phase (see section 2.3). In-cloud precipitation is defined as precipitation that is developed in clouds but does not reach the surface at the ship. In-cloud precipitation is considered when the minimum radar reflectivity profile above 0.2 km exceeds -15 dBZ (lower threshold for drizzle), and the disdrometer detects dry conditions at the surface. We note that in-cloud precipitation has the potential to advect far downwind in the strong westerly winds of the SO storm track. Thus in-cloud precipitation does not necessarily indicate sub-cloud evaporation.

3.1 Cloud radar statistics under the seven K-Means clusters

The CFTD/CFAD of the W1 cluster (warm air advection in the pre-frontal regions north of ocean polar front) is characterized by a broad distribution of clouds across the temperature range from -30 to 15^{o}C, reaching altitudes up to almost 8 km (Figure 2a, c). The large fraction of warm clouds (greater than 0^{o}C) features a wide reflectivity spectrum between -25 and 10 dBZ, indicating a large variability ranging from non-precipitating to drizzling, to precipitating clouds. Precipitating warm clouds typically have Doppler velocity less than -3 ms^{-1} with median reflectivities higher than 5 dBZ, indicating some heavy falls. Drizzling and non-precipitating warm clouds correspond to a weaker Doppler velocity; between 0 and -1 ms^{-1} (Figure 2b, d). The average melting layer height is identified at around 3 km, the highest of all clusters (Figure 2c, d). Between -10 and 0^{o}C, precipitation-size particles dominate the reflectivities, with values between -10 and 5 dBZ (likely mixed-phase clouds), whereas clouds at temperatures less than -10^{o}C have a core of strong reflectivities from -10 to 0 dBZ. The increase of reflectivity towards higher temperatures (between -15 and about -0^{o}C) suggests ice particle growth likely via aggregation. Evidence of large ice particles (above 5 dBZ) associated with convective updrafts can be identified with Doppler velocities around 1 ms^{-1} at -20^{o}C. Far less frequent, non-precipitating ice clouds (most likely cirrus) are also present, as shown in the second branch with temperatures below -10^{o}C and reflectivities lower than -15 dBZ. Surface precipitation is recorded approx. 6% of the time, predominantly very light/light precipitation (below 0.99 mm/hr) and liquid phase (Table 2). Overall, these cloud and precipitation characteristics are consistent with warm air advection featuring a warm and moist troposphere.

The high-pressure cluster M1 (Figures 2e-h) features the lowest cloud cover percentage (CC 62%). A discontinuous dipole-like structure is evident in the CFTD/CFADs, representing two dominant disconnected cloud types: non-/lightly precipitating boundary layer clouds (likely closed mesoscale cellular convection as reported in Lang et al. (2020), Lang et al. (2022)) with Doppler velocities between 0 to -2 ms^{-1}; and mid-level clouds with in-cloud precipitation that does not reach the lower troposphere. The latter features a high concentration around -20^{o}C and -5 dBZ, which suggests small precipitation-size particles, possibly mixed phase. Cirrus clouds are also present (below -30^{o}C and with reflectivities below -10 dBZ). Precipitation measurements suggest virtually dry conditions at the surface, and in-cloud precipitation about 7% of the time (Table 2). The disdrometer measurements and the CFAD/CFTD cloud patterns are generally consistent with the M1 conditions inferred from the average sounding profile (Figure 3 in Truong et al. (2020)).

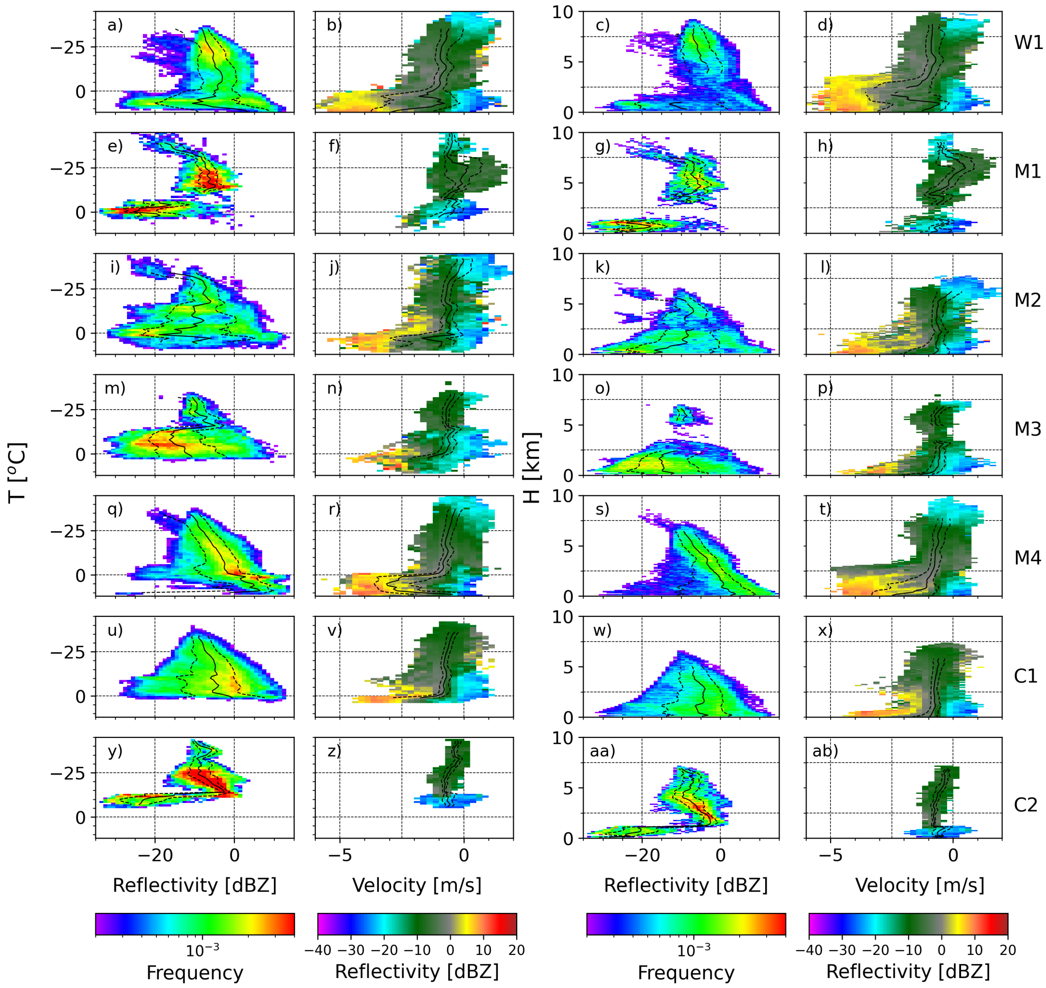


Figure 2. From left to right BASTA cloud radar reflectivity Contour Frequency by Temperature Diagram (CFTD) and reflectivity median value as a function of temperature and Doppler velocity, followed by the same figures for altitude. Dotted lines are the 25% and 75% percentile, line the 50% percentile of the abscissa variable. From top to bottom, clusters W1 (warm air advection), M1 (high pressure), M2 (cold front), M3 (post-front), M4 (warm front), C1 (high-latitude cyclone center), and C2 (coastal Antarctica). All during the CAPRICORN I and II, synoptic conditions are classified by a k-means clustering method.

Moving to the cold front (M2) cluster, the radar reflectivity CFTD/CFAD has a broad distribution (-25 to 15 dBZ), spanning from temperatures above 10^{o}C down to about -15^{o}C, hinting at a wide range of hydrometeor types/sizes, cloud types, microphysical processes, and convective/stratiform precipitation (Figures 2i, k). Strong radar reflectivities (greater than 5 dBZ) associated with Doppler velocity around/above 1 ms^{-1} are present between -20 and -5^{o}C, consistent with strong ice production within the convective updraft. There are also some fast-falling particles, faster than -3 m/s, with reflectivities around 5 dBZ (Figure 2j, l). Between -30^{o}C and -15^{o}C, the slope of the mean reflectivity suggests ice growth. At around -35^{o}C, the low reflectivities and narrow frequency distribution are consistent with ice deposition. Although one might expect considerable precipitation for the cold front cluster, the disdrometer indicates surface precipitation only 5% of the time: predominantly light (55%) and liquid (89%), followed by mixed phase (18%). The in-cloud precipitation is also only present ∼7% of the time. While somewhat counter-intuitive, the analysis suggests that the M2 cluster might be dominated by pre-frontal multi-level clouds that do not actively produce intense precipitation.

Table 2. 1 minute resolution OceanRAIN disdrometer surface precipitating time (P_s [%]), precipitating median± Interquartile range intensity ($\widetilde{I}$±IQR [mm/hr]), and percentages of surface very light (P_{vl}), light (P_l), moderate (P_m), intense (P_i), and extreme (P_e), as well as the percentage of liquid, snow and mixed-phase precipitation. Precipitating time inside clouds, and not reaching the surface (P_c [%]) estimated from the 1 minute mean W-band cloud radar. Cloud clover (CC) defined using the cloud mask from the cloud radar/lidar dataset on a 1-min resolution. All during CAPRICORN I and II classified by different synoptic scenarios: k-means clustering, distance to cyclone and front. Note that the number of soundings (S) used for the identification of each scenario is highlighted.

		Disdrometer										**Radar-lidar**	
Synoptic	S	P_s [%]	$\widetilde{I} \pm IQR$ [mm/hr]	P_{vl} [%]	P_l [%]	P_m [%]	P_i [%]	P_e [%]	Liquid [%]	Snow [%]	Mixed [%]	P_c [%]	CC [%]
W1	39	6.30	0.27±0.9	31.06	44.71	23.29	0.94	0.00	100.00	0.00	0.00	13.08	83.80
M1	26	1.33	0.05±0.04	95.08	4.92	0.00	0.00	0.00	100.00	0.00	0.00	6.53	61.89
M2	41	4.54	0.24±0.55	28.35	55.49	15.85	0.30	0.00	89.02	0.61	10.37	6.69	71.86
M3	37	4.75	0.1±0.34	49.21	36.19	11.75	2.86	0.00	92.06	1.27	6.67	9.50	88.38
M4	21	44.92	0.37±0.78	28.10	51.36	20.48	0.00	0.06	96.81	1.77	1.42	10.60	92.19
C1	91	20.05	0.15±0.52	40.17	44.22	13.19	1.50	0.91	47.13	40.39	12.47	7.19	86.95
C2	11	0.00	0.00±0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	21.57	85.41
Q0	57	23.15	0.21±0.52	32.38	53.12	14.24	0.22	0.04	67.98	21.76	10.26	8.50	92.22
Q1	40	14.79	0.28±0.77	35.17	45.54	19.09	0.10	0.10	90.21	4.84	4.94	10.25	70.70
Q2	39	10.57	0.17±0.88	40.91	35.81	20.66	2.62	0.00	94.49	2.75	2.75	7.78	84.45
Q3	36	6.72	0.09±0.1	55.89	39.26	4.62	0.23	0.00	25.87	73.67	0.46	8.14	76.91
Q4	29	18.26	0.55±1.04	15.55	53.89	23.84	3.78	2.94	78.00	5.57	17.44	12.03	87.50
Pre	45	10.27	0.19±0.42	30.59	63.46	5.94	0.00	0.00	71.30	28.70	0.00	8.37	82.30
Post	87	15.69	0.20±0.66	34.47	46.62	17.95	0.88	0.08	72.55	16.60	10.84	7.57	78.02
Frontal	26	23.13	0.40±0.93	32.44	43.19	23.35	1.02	0.00	73.21	17.05	9.73	3.93	95.38

The radar reflectivity CFTD/CFAD for the cold post-frontal (M3) cluster has a broad distribution in the lower troposphere, which narrows significantly towards higher (lower) altitudes (temperatures), signaling the dominance of a relatively shallow cloud population at temperatures greater than -15^{o}C and a detached cloud between -35 and -15^{o}C (Figure 2m, o). While non-precipitating clouds prevail in the shallow cloud regime, there are strong radar reflectivities (greater than 5 dBZ) associated with strong negative Doppler velocities (smaller than -2 ms^{-1}) between -10 and 0^{o}C, consistent with the formation of large particles (Figure 2n, p). Such characteristics are congruent with in-situ observations in the Hallett-Mossop temperature zone shown in several previous studies for a similar synoptic environment (e.g. Huang et al. (2017), Huang et al. (2021)), commonly associated with the open mesoscale cellular convection (Lang et al., 2021, 2022). Positive Doppler velocities indicate updrafts (convection) are stronger than for the M1 cluster. Surface precipitation of this cluster is recorded 5% of the time, featuring dominantly very light/light precipitation and dominantly liquid phase. The bulk of the clouds residing below 2.5 km is consistent with a strong temperature inversion at approx. 780 hPa for the M3 cluster (Figure 3 in Truong et al. (2020)).

The M4 cluster (warm front) produces the largest cloud cover (92%). The radar reflectivity CFTD/CFAD showcases the typical arc shape of large-scale deep convection, where the mean reflectivity increases monotonically towards higher temperatures and lower altitudes, which also indicates the likely presence of aggregation (Figure 2q, s). There is a visible enhancement of reflectivity below the melting level in the CFTD, but not evident in the CFAD. This pattern suggests that the melting level in the M4 soundings varies across a range of altitudes. The frequency distribution in M4 is narrower than that in the M2 (cold front) cluster, indicating more uniform microphysical processes (likely dominated by aggregation, mainly between -15 and 0^{o}C) as well as hydrometeor types. Strong reflectivity values in the warm rain region indicate precipitation with negative velocities between -3 and -5 m s^{-1} (Figure 2q-t). This cluster registers the highest precipitation percentage (approx. 45% at the surface and 11% in clouds). The disdrometer records predominantly liquid phase (both warm rain and SLW). Overall the disdrometer and CFAD/CFTD information is consistent with a typical warm front scenario as discussed in Truong et al. (2020). The M4 and W1 clusters share some similarities in the CFAD/CFTD patterns, based on the nature of these two clusters we hypothesize that the W1 clouds evolve into M4 clouds as it moves further south. Additional analyses would be needed to confirm this process.

The radar reflectivity CFTD/CFAD for the C1 cluster (high-latitude cyclone over the SO) feature an absence of warm clouds but a broad spectrum below freezing temperature, which indicates a wide variety of hydrometeors (Figure 2u-x). Unlike previous clusters, there is no clear division between the cloud layers. Similar to M3, some of the high reflectivities coincide with fast falling velocities (smaller than -2 ms^{-1}) within the Hallett-Mossop temperature zone, possibly indicating the presence of rimed particles and/or graupel, although further observations are needed to confirm the presence of this mechanism. High reflectivities associated with a Doppler velocity of around 1 ms^{-1} were also detected close to -15^{o}C, suggestive of active convection. This is consistent with the expected behavior of C1, which resides typically close to a cyclone center. Precipitation data show that C1 has the highest mean intensity from all clusters, although the absolute values are subject to higher uncertainties given the highest fraction of snow detected at the surface (about 40%).

Contrasting to the C1 cluster, the coastal Antarctica C2 cluster CFTD/CFAD indicates two distinct cold cloud types (Figure 2y, aa). One is the non-precipitating shallow clouds (below 1 km or greater than -15^{o}C) with radar reflectivities below -15 dBZ and Doppler velocities between -2 and 0.5 ms^{-1} (Figure 2z, ab). The other represents the mid-level cloud type which is more prevalent. The magnitude and slope of the reflectivity frequencies between -30 to -15^{o}C once again imply ice growth. The C2 cluster has no precipitation at the surface, consistent with the low humidity in the lower troposphere reported in Truong et al. (2020). However, in-cloud precipitation (not reaching the surface) is present almost 22% of the time in the mid-level clouds (Table 2), which suggests strong evaporation and/or sublimation in the lower troposphere, likely associated with the descending, dry, katabatic winds off the Antarctic coast. Note that the number of soundings for this cluster is relatively small (11) compared to the others.

It should be noted that the cluster classification performed by Truong et al. (2020) focused on the lower free troposphere, only employing soundings information up to the 700 hPa level. In general, the upper troposphere has stronger winds and is not necessarily directly linked to the lower troposphere. We note the common presences of clouds from 5 to 8km along the storm track (M1-M4). The strong winds in the upper-troposphere can readily advect clouds across the clusters. We also note that the cloud radar might under-detect the thin, non-precipitating liquid clouds, particularly in the lower troposphere, but this limitation is not expected to affect our key findings.

3.2 Cloud radar statistics under Cyclone Quadrants conditions

Moving to the analysis with respect to cyclone quadrants, overall the CFAD/CFTD patterns corresponding to each quadrant are less distinct than those segregated by clusters (Section 3.1). Nevertheless, the zero quadrant (Q0) reflectivity CFTD/CFAD characteristics largely resemble the C1 counterparts, except that a small fraction of warm clouds are also present. This may be explained by the fact that Q0 includes all cyclone centers detected during the field campaigns, not only those limited to the high-latitude SO where clouds are generally much colder. Q0 also includes a portion of M2 (18%) and M4 (11%) clusters where warm clouds are not uncommon. The disdrometer information is consistent with the CFTD/CFAD analysis for Q0 in terms of precipitation characteristics.

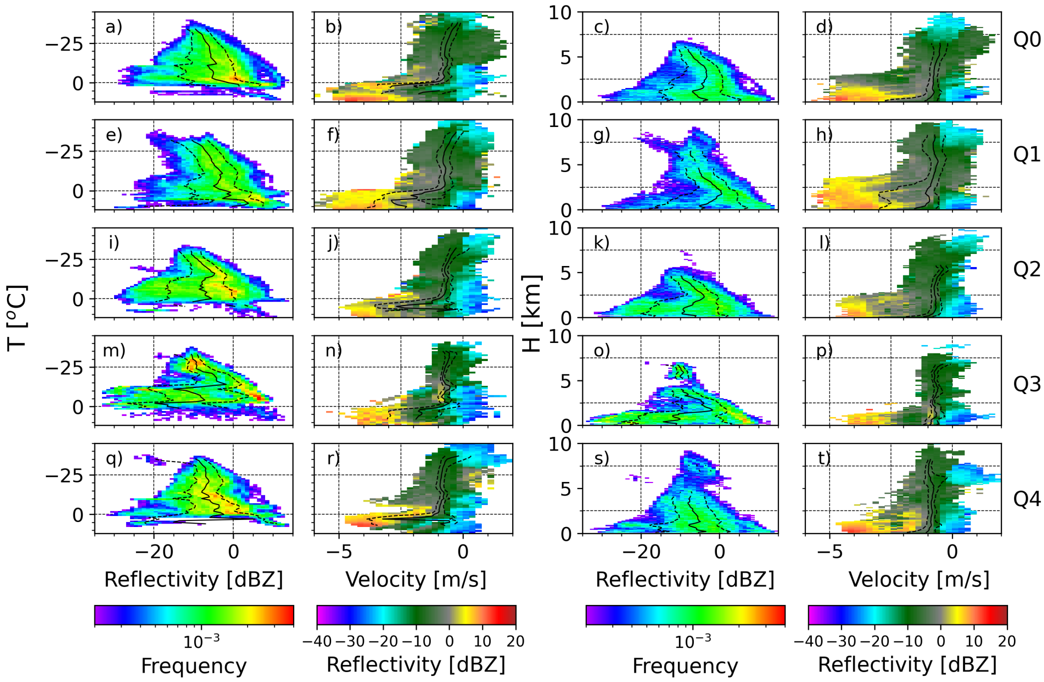


Figure 3. Same as Figure 2 but segregated by cyclone sectors.

Q1 resembles the M4 and M2 clusters, with differences noted due to the large variability of the cold/warm front location with respect to the cyclone center. Thus, the Q1 quadrant represents only a subset of the total number of cold and warm frontal conditions, whereas the M2 and M4 clusters showcase a more unambiguous representation. The Q1 CFTD/CFAD radar reflectivity has an arc shape between 5 and -10 dBZ (typical of deep convection; Figures 3e-h). Warm clouds are mainly precipitating clouds with strong Doppler velocities between -6 and -2 ms^{-1}. Between -5 and 0^{o}C there is a band ranging from 0 to -15 dBZ, suggesting mixed-phase conditions.

Q2 is likely dominated by shallow clouds at temperatures greater than -15^{o}C (3 km). The CFAD/CFTD distributions for Q2 are similar to those of the M3 cluster, which is expected since the M3 cluster represents the post-frontal conditions. Several high-frequency cores are present between -15 and 0^oC, indicating the presence of a variety of microphysical mechanisms (Figure 3i-l). Strong radar reflectivities (around 5 dBZ) are seen with Doppler velocities greater than -2 ms^{-1}, indicating the presence of dense particles (e.g. possibly graupel or rimed particles, as also noted for M3), as well as a mixture of liquid and ice precipitation. The surface precipitation characteristics also resemble those of M3.

Q3 and Q4 conditions are less explored in the literature. Our analysis suggests that Q3 is a hybrid of C1 and M3 conditions (Figure 3m, o) while Q4 most commonly represents C1 and, to a lesser extent, W1 (Figure 3q-t.). Interestingly, however, Q3 has the lowest precipitation intensity among all cyclone sectors, while Q4 features the highest intensity. Q3 surface precipitation is dominated by snow, while liquid phase precipitation is most commonly observed for Q4 (mostly SLW). This may not be a surprise given the colder nature of Q3 associated with a stronger southerly winds.

It is worth noting that the 15^o box per quadrant may not be the best threshold for discriminating the cyclone conditions, as the nearest cyclone may not necessarily be the dominant feature at a given sounding. Nevertheless, we tested three different sizes (from 10 to 20^o per quadrant) and the 15^o was the distance that allowed a good number of sounding per quadrant. Our results are not qualitatively impacted by this threshold.

3.3 Cloud radar statistics under cold Front distance conditions

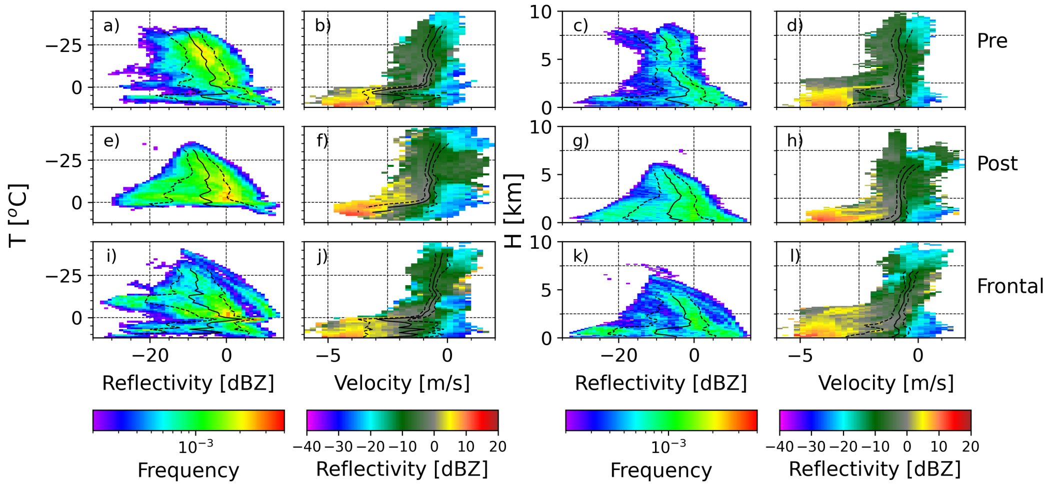


Figure 4. Same as Figure 2 but segregated by distance to cold front.

The analysis associated with cold front composites has significantly fewer soundings compared to the k-means clustering analysis (108 less). The pre-, post- and frontal classifications all have a hybrid of different clusters, suggesting that this methodology has limited skills in segregating cloud regimes.

The radar reflectivity CFTD/CFAD in the pre-frontal condition resemble that of the W1 cluster (Figure 4). It should be noted, however, that the W1 cluster only represents the pre-frontal air mass with strong warm advection north of the ocean polar front, while the pre-frontal conditions could happen across latitudes. The post-frontal CFTD/CFAD distributions contain mainly some of the C1, M2, and M3. Finally, the cold frontal condition is composed primarily of almost the same proportion of C1 and W1 clusters.

Turning to precipitation, the pre-frontal condition has a higher fraction of warm rain, evidenced by the high reflectivity values at Doppler velocities stronger than -3 ms^{-1}. This classification also has the highest fraction of snow, according to the surface measurements. The frontal conditions have the highest precipitation intensity among the three, which is to be expected given the dominance of C1 (31%) and W1 (27%) clusters.

To summarize, the K-means clustering methodology is shown to be the most skillful in sorting/defining cloud and precipitation regimes. The cyclone and frontal composite methods produced more ambiguous results, despite their extensive applications in the literature. In general, clouds in the upper free troposphere are less distinct across all classifications, which is not unexpected given the common decoupling of the upper troposphere dynamics from the surface meteorology that is used to drive the thermodynamics and synoptic classifications.

4 Case study: GV aircraft microphysical characteristics

In this section, we analyze a segment of the third flight (RF03) of the SOCRATES mission to evaluate, as a case study, our interpretation of remote-sensing observations from the CAPRICORN campaign. We selected the period when the GV aircraft was closest to the RV Investigator (between 2018-01-23 00:50 and 01:18 UTC), which is defined by the time the GV aircraft did one ascending (descending) leg towards (away from) the RV Investigator, sampling the same synoptic conditions (Figure 5). Since the shipborne cloud radar has a lower temporal resolution than the airborne one, we selected an extended period for the comparison while ensuring that the ship was under the same synoptic conditions (between 2018-01-22 23:40 and 2018-01-23 02:50 UTC).

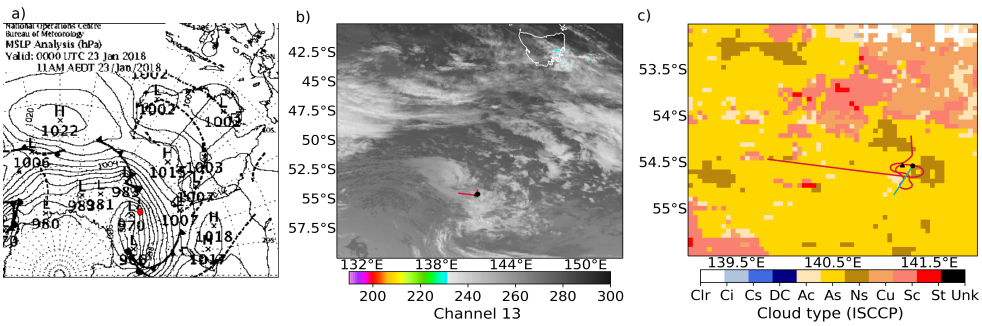


Figure 5. a) Mean Sea level Pressure (MSLP) analysis of the Australian Bureau of Meteorology (BoM) for 2018-01-23 00 UTC. Red dot indicates the approximate location of the RV investigator and the GV aircraft. b) Himawari-8 brightness temperature in Kelvin (channel 13), and c) cloud type classification from the Japan Aerospace Exploration Agency for 2018-01-23 00:50 UTC; black triangle (square) shows the location of the dropsonde (radiosonde). The red line indicates the GV aircraft track during the period (2018-01-23 00:50 to 01:18 UTC). Blue line represents the RV Investigator location while measuring the same type(s) of clouds (2018-01-22 23:40 and 2018-01-23 02:50 UTC).

Flight RF03 included one constant leg in the vicinity of the ship lasting for about 7 minutes at 6 km, launching a dropsonde west of the RV Investigator at 2018-01-23 01:02 UTC. The flight dropsonde is classified as a M4 cluster. Equally, the radiosonde from the RV Investigator, which was launched about 10 minutes before the approach of the aircraft (2018-01-23 00:52 UTC), is also classified as M4 (Figure 6). This is also consistent with the frontal and cyclone detection and the Himawari-8 satellite cloud type classification, with Altostratus, Nimbostratus and occasionally multi-layer cloud systems dominating the sampling area (Figure 5). The Mean Sea Level Pressure (MSLP) analysis chart from the BoM indicates the ship and the aircraft were located near a warm front at 2018-01-23 00:00 UTC, although at this time a low pressure center to the south was in close proximity. Note that the MSLP snapshot is earlier than the sampling period and the warm front would have been closer to the RV Investigator by the sampling time.

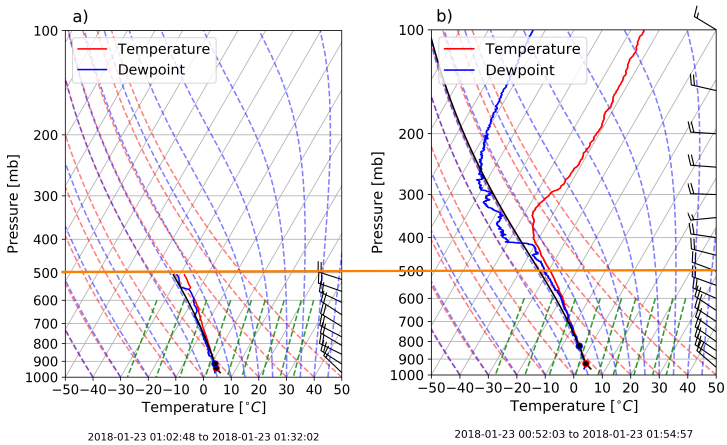


Figure 6. a) Dropsonde sounding profile from the GV aircraft launched at 2018-01-23 01:02 UTC. b) Radiosonde sounding released from the RV Investigator at 2018-01-23 00:52 UTC. Orange line indicates the altitude of the GV aircraft.

When using the other two synoptic classifications (cyclone and frontal composites), the sampled areas were in Q0 (at an approximate distance of 4^o north 0.04^o west of the cyclone center) and pre-frontal (at a distance of about 4^o ahead of the cold front) conditions. When the ship and the aircraft were close, the radiosonde, the dropsonde, the radar and lidar observations show characteristics comparable to the M4 cluster description. Both sondes indicate strong north-westerly winds and saturated conditions below 500 hPa, indicating the presence of precipitating clouds (Figure 6). The disdrometer aboard the RV Investigator recorded primarily liquid precipitation with an intensity between very light to light and a median precipitation intensity of 0.14 ± 0.31 mm/hr. This is weaker than the median intensity in the M4 cluster, but still within the natural variability (0.21 $\pm$ 0.52 mm/hr, Table 2).

The HIAPER radar observations show that the sampled clouds were commonly precipitating (drizzle starts at -15 dBZ), with a melting layer located at around 600m above sea level (Figure 7). The Doppler velocity, ranging from 0.28 and -1.38 ms^{-1}, is predominantly negative and decreases further when reaching the melting layer (down to values near -5 ms^{-1}; Figure 7b). The radar reflectivity CFAD/CFTD features a broad distribution, suggesting a large variety of hydrometeors and microphysical types/processes (Figure 8). Three modes of high frequency are visible: the first mode lies between -30 to -10^{o}C (2.5 to 5 km), characterized by reflectivity increasing from -25 to 0 dBZ towards higher temperatures, likely suggesting particle growth primarily via aggregation. The second mode is located at -10 and -5^{o}C (0.7 to 2 km), with reflectivities around -12 and 0 dBZ, also suggesting ice growth. The third mode is a small core near the melting layer, likely indicating the coexistence of SLW and small ice particles. In the warm clouds, the radar reflectivities peak in the range of -15 to 0 dBZ, indicating lightly precipitating clouds. Although less frequent, the cloud radar also detects strong precipitation in the warm cloud region, where reflectivities above 5 dBZ, with Doppler velocities stronger than -3 ms^{-1}, are present near the melting layer (Figures 8 a and c). The shipborne CFAD/CFTD patterns share some similarities with the GV counterparts, although the modes are less distinct in the former probably due to the lower time resolution of the observations. Both the airborne and shipborne CFAD/CFTD patterns provide evidence of deep cloud layer(s) and particle growth towards lower altitudes via multiple mechanisms, broadly consistent with the M4 cluster and pre-frontal composite results as discussed in Section 3.

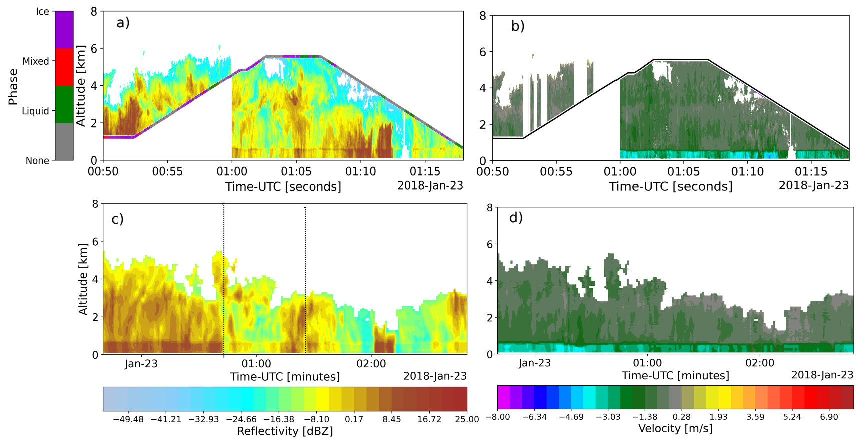


Figure 7. Upper panel shows the HIAPER (Aircraft) data from a) the cloud radar reflectivity (dBZ) (Contours), colored line indicates the GV altitude and phase classification according to Schima et al. (2022, In Preparation); and b) Doppler velocity between 2018-01-23 00:50 to 01:18 UTC. Lower panel indicates the ship based measurements of the BASTA c) cloud radar reflectivity (dBZ; dashed lines are the HIAPER time period), and d) Doppler velocity between 2018-01-22 23:40 and 2018-01-23 02:50 UTC. Note that the RV Investigator need more time to sample a similar area than the GV aircraft.

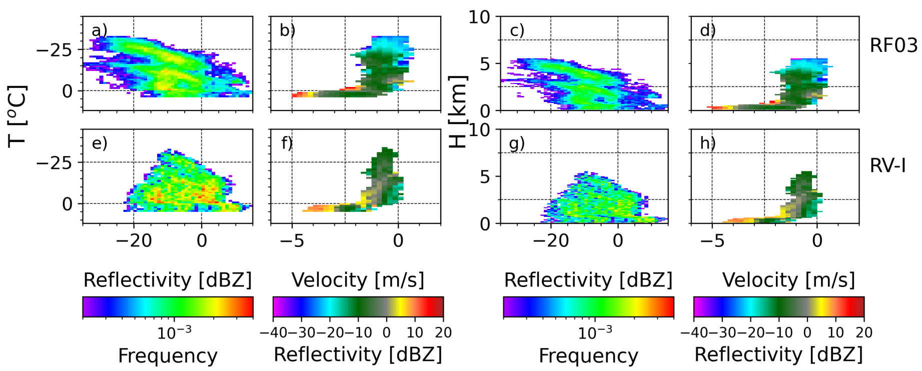


Figure 8. Same as Figure 2 but for the HIAPER cloud radar during the third flight of the SOCRATES field campaign (RF03) and the BASTA cloud radar during the CAPRICORN field campaign (RV-I). Note the time periods are different (2018-01-23 00:50 to 01:18 UTC vs 2018-01-22 23:40 and 2018-01-23 02:50 UTC; but both are under the same synoptic conditions (and cloud type).

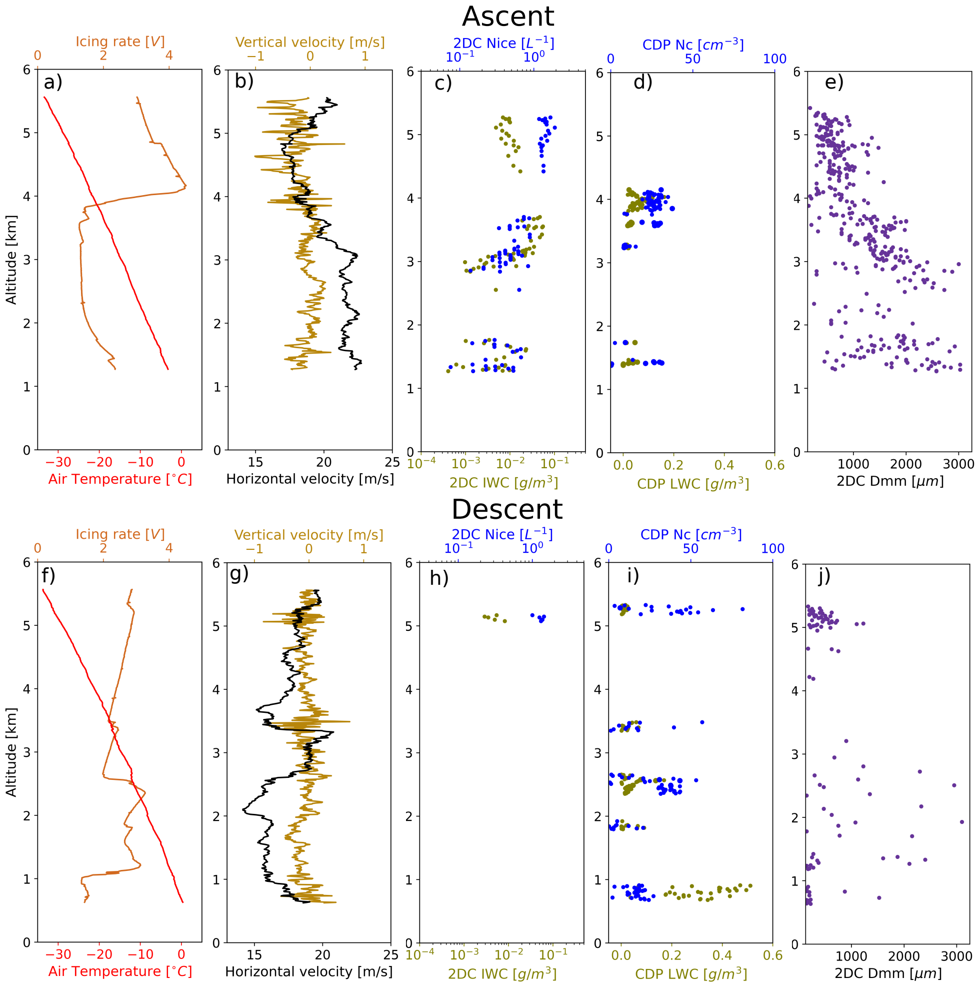


Figure 9. a,f) Temperature (red) and Supercooled Liquid Water (SLW, brown) proxy. b, g) Vertical (yellow) and horizontal (black) wind speed. c, h) 2DC Ice number concentration (Nice, blue) and Ice Water Content (IWC, green) derived for ice phase clouds only, d, i) CDP droplet concentration (Nc, blue) and Liquid Water Content (LWC, green) for mixed and liquid phase clouds. e, j) 2DC Median mass diameter (Dmm). For one ascending, descending leg during the GV aircaft overflight from the RV Investigator. Only values where the Total Water Content is > 0.005 g/m^-3 are plotted.

The in-situ aircraft observations provide direct evidence of the microphysical properties that can help evaluate our interpretation from Figure 8. Here we examine one ascending and one descending leg in the proximity of the RV Investigator. The ascending leg penetrated through a deep cloud near a warm front, whereas the descending leg seemed to be coming through multi-layer clouds at the cloud edge and was not sampling much in cloud (Figure 7). The in-situ phase classification based on Schima et al. (2022, In Preparation) indicates that ice phase was dominant along the ascent profile, about 76% of the in-cloud time, largely coinciding with the enhanced radar reflectivities recorded in the vicinity of the flight path. The descent profile, on the other hand, features an intermittent presence of liquid or ice phase, consistent with the weaker reflectivities and the more tenuous structure of the cloud layers. The two vertical profiles show that the 2DC median mass diameter (Dmm) varies in the range between 150 and 3200 μm, suggesting the common presence of large particles, particularly along the ascent profile (Figure 9). Consistently, the 2DC instrument detected ice number concentrations (Nice) throughout the ascent profile (especially around 1.5 km, 3 to 3.7 km, and near 5.3 km) in the range of $7.5 * 10^{-5}$ to $1.9 * 10^{-3} cm^{-3}$, whereas little Nice was recorded during the descending leg (Figures 9c and i, note that the Nice is shown for ice phase clouds only due to the large uncertainties in the estimated Nice for mixed phase using the 2DC). It should be noted that the Schima et al. (2022, In Preparation) phase classification indicates more frequent ice phase in the descent profile than Figure 9h, because the classification used a combination of several cloud probes, not only the 2DC where only particles sizes greater than $200\mu m$ are considered. Liquid water content (LWC) profiles measured by the CDP probe are shown for liquid and mixed phase clouds (Figures 9d and i), providing more evidence on the phase characteristics. The descending leg further showcased typical boundary layer clouds (below 1 km; given the lower reached altitude).

The PHIPS particle habit images (Figure 10) indicate the frequent presence of rosettes at about 6 km or between -30 and -25^{o}C. Some of the rosettes were bullet rosettes, while others have more complex structures. Between -20 and -10^oC, the ice crystals were columns with some plate-like structures, rimed crystals, and ice of irregular habits (Figure 10). Between -5 and 0^{o}C rimed particles and needles become more dominant, while water and rain droplets were typical at temperatures above 0^{o}C. Snapshots of the particle images recorded by the Fast 2DC particle probe at different altitudes/temperatures also indicate a large variety of particle habits, broadly consistent with those recorded by the PHIPS instrument. Overall, the observed ice habits are consistent with what has been reported in the literature for deep clouds over mid and high latitude oceans (Bailey & Hallet, 2009; Kikuchi et al., 2013). Inspection of the 2DC images did not show evidence for pervasive amounts of supercooled drizzle (SLD). However, for small time periods there is a possibility that small amounts of SLD was present due to ambiguity in interpreting the shapes of the 2DC images, and hence in the phase.

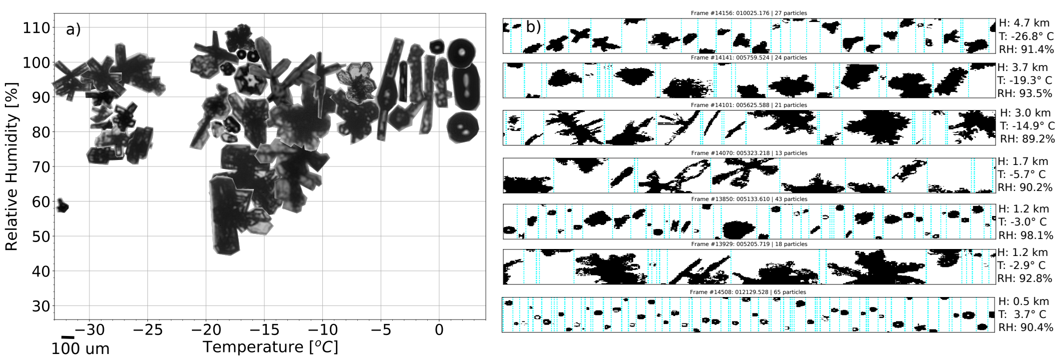


Figure 10. Particle images obtained by a) the Particle Habit Imaging and Polar Scattering (PHIPS-HALO) stereo imaging instrument. Images are represented as a function of temperature and relative humidity. b) The Fast 2DC probe. Both during the third flight of SOCRATES (RF03) in the vicinity of the RV Investigator (between 2018-01-23 00:20 to 01:29 UTC).

Overall, despite the somewhat non-classic warm front that was encountered during the overflight, the coincident airborne and shipborne radar reflectivity CFAD/CFTD analyses are largely consistent with the composite results in Section 3 for the M4 cluster. The limited in-situ cloud properties also support our interpretations of the CFAD/CFTD analysis and associated microphysical processes, although more data is necessary to enhance the evaluation for other clusters.

5 Conclusions and Discussion

Motivated by the need to better understand the Southern Ocean (SO) cloud and precipitation systems, this research capitalized on recent field observations from the Clouds Aerosols Precipitation Radiation and atmospheric Composition Over the Southern Ocean (CAPRICORN) I and II to examine the macro- and microphysical characteristics of the clouds and precipitation, under different thermodynamic and synoptic atmospheric conditions. Aircraft observations collected by research flight RF03 from the Southern Ocean Clouds Radiation Aerosol Transport Experimental Study (SOCRATES) were used to complement the analysis and to evaluate the interpretations of the shipborne remote-sensing information. Key findings of this study include:

- Distinct cloud and precipitation regimes are found to correspond to the seven thermodynamic clusters established in Truong et al. (2020), over the Australian sector of the Southern Ocean. In contrast, cloud and precipitation regimes are less well defined using the cyclone and (cold) front compositing methods.
- The warm front (M4) and the high-latitude cyclone (C1) clusters possess the highest fractions of surface precipitation, with the former being dominated by warm rain and the latter featuring the largest fraction of snow. Evidence suggests that ice aggregation in relatively deep convection likely dominates the particle growth in M4, while multiple microphysical mechanisms within cold clouds are present in C1.
- The driest surface conditions are found to be associated with the Coastal Antarctica (C2) and high pressure (M1) clusters. Both represent a discontinuous dipole-like structure in the cloud vertical profiles, where low-level clouds are primarily non-precipitating.
- The warm air advection cluster (W1) is characterized by a variety of cloud processes featuring a warm, deep and moist troposphere. Unlike M4, only warm rain with a relatively weak intensity is recorded at the surface.
- The cold frontal (M2) and post-frontal (M3) clusters feature similar surface precipitation characteristics. However, the M2 cluster represents a higher variability of ice processes and cloud types, while M3 has a high frequency of mixed phase clouds between -15 and 0 ^{o}C.
- The case study using in-situ observations from SOCRATES generally supports the interpretations of key microphsyical processes using the cloud radar profiles. A variety of ice habits are observed across a wide range of temperatures down to -35^{o}C under the M4 cluster.

The M3 cluster, which represents the cold sector of the cyclones over the mid-latitude SO, is characterized by the predominance of shallow clouds (below 3km and higher than -15^{o}C) that are composed primarily of non- to weakly precipitating particles in the lower troposphere. These clouds have been reported to be most poorly simulated in weather and climate model at all scales, constituting a leading contributor to the shortwave radiative biases (Bodas-Salcedo et al., 2012, 2014, 2016). However, it is worth noting that recent research has documented the frequent presence of both the open and closed Mesoscale Cellular Convective (MCC) clouds in this environment (Lang et al., 2021, 2022), with contrasting cloud phase composition and precipitation rates (Ahn et al., 2017; Huang et al., 2017, 2021). Further analysis into the oceanic and atmospheric conditions would be necessary to refine our understanding of the associated cloud controlling factors. However, we hypothesize that common presence of non- to weakly precipitating closed MCC clouds should influence by permitting less incoming radiation to the surface.

The cloud and precipitation characteristics associated with the high-latitude cyclones (C1) are intriguing, as the geographical distribution of this cluster is spatially more correlated with the locations of the largest radiative biases in climate model simulations

(Bodas-Salcedo et al., 2012). With the absence of warm clouds, ice (i.e. cold cloud) processes are expected to be dominant in this environment. Our analysis presents evidence of glaciation processes in these clouds, which are further supported by the largest fraction of snowfall recorded at the surface. This creates an open question as how to reconcile the prevailing argument on the lack of supercooled liquid water in climate models and the active glaciation evident in the ship observations over the high-latitude SO. Equally interesting is the Coastal Antarctica (C2) cluster which is strongly dominated by non-precipitating low clouds that are presumably mostly SLW, despite the precipitating clouds aloft. This is in sharp contrast to C1, and may be associated with the drying effect of the katabatic winds as discussed in Truong et al. (2020). Given that C2 cluster had much fewer soundings from the CAPRICORN experiments, additional data would be beneficial for a better characterization of this environment.

This study is the first, to our knowledge, to couple cloud and precipitation fields with the thermodynamic and synoptic conditions over the remote SO using newly available field observations. Our analysis shows that, to a large extent, clouds and the ensuant precipitation can be patterned by these atmospheric conditions. Leading microphysical processes are also inferred from the cloud radar reflectivites, Doppler velocity and temperature ranges; however, these interpretations should only be treated as a first-order, qualitative estimates that are in line with the given synoptic and thermodynamical conditions. Different ice habits are characterized by distinct falling speeds, which are difficult to distinguish using a single-frequency cloud radar. More in-situ data, together with innovative combinations of multiple remote-sensing observations, are needed to validate these interpretations. Future studies should also consider evaluating the realism of the identified relationships in model simulations, with the aid of instrument simulators.

Finally, while the cold-air sector of an extratropical cyclone possesses a large climatological-mean bias, the day-to-day processes governing how the clouds respond to dynamical perturbations are more flawed in the anticyclones and the frontal environments, as elaborated in a recent study where output from 10 models that participated in CMIP5 were analyzed (Kelleher & Grise, 2019). Here our clustering framework would allow for a more direct identification of processes that may be inherently misrepresented in models.

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