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ARM

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Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE) Field Campaign Report

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Executive Summary

The Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE) was conducted successfully between 1 December 2019 and 31 May 2020 around the Norwegian Sea. COMBLE deployed the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) first Mobile Facility (AMF1) along the coast of northern Scandinavia, at an arctic latitude (70°N), and an array of additional instruments on Bear Island (75°N) in the Norwegian Sea. The instruments deployed at these two sites collected a large array of in situ and remote-sensing observations of atmospheric conditions, clouds, precipitation, and aerosol.

The main objective of COMBLE is to quantify the properties of shallow convective clouds that develop as part of an air-mass transformation process when cold air blows over open water. The two COMBLE sites are located at ~1,200 km and ~500 km from the cold source, i.e., arctic ice edge, respectively. Specifically, COMBLE aims to:

1. describe *the fetch-dependent mesoscale organization* of clouds, precipitation, and radiation in cold-air outbreaks (CAOs), including linear and cellular convection.

2. describe *the surface fluxes of heat, moisture, and momentum, and vertical profiles of temperature, humidity, wind, and turbulent kinetic energy* within and between convective cells as a function of fetch.

3. describe the *profiles of vertical velocity, cloud properties* (liquid and ice mass, cloud particle sizes, phases and shapes), as well as *precipitation and radiation* in boundary-layer convection.

4. examine the impact of varying *aerosol conditions* in the upstream Arctic boundary layer, as well as marine aerosol sources and anthropogenic pollution, on ice initiation, cloud liquid water, snow growth, and radiative fluxes in a range of wind and temperature regimes.

5. provide *integrated data sets of dynamical, thermodynamic, and microphysical characteristics of the CAO boundary layer*, including cloud and aerosol properties, that will enable constraining high-resolution numerical simulations, developing process-level understanding of shallow convective clouds in CAOs, and, subsequently, evaluating and improving representations of shallow convection in CAOs in weather and climate models.

Overall, COMBLE was a great success, notwithstanding the pandemic. The AMF instruments performed very well for the duration of the campaign. Met Norway assisted in various ways, including the launching of 3-hourly radiosondes from Bear Island (ENBJ) and Andenes (ENAN) very close to the AMF1 site. Three European airborne campaigns were planned in the vicinity of COMBLE sites during the campaign, specifically in March and early April 2021. Unfortunately all three had to be cancelled last-minute due to the COVID pandemic, so COMBLE lacks in situ cloud information. The Airborne CAO (ACAO) campaign (Principal Investigators: Steven Abel and Paul Field, co-Principal Investigators in COMBLE) were to fly the British Met Office/Natural Environment Research Council Facility for Airborne

Atmospheric Measurements (FAAM) BAE-146 aircraft, equipped with an array of aerosol, cloud, and precipitation sizing and imaging probes, along RHI scans by the AMF1 Ka and W-band radars during CAOs. The Norwegian Aerosol, Cloud, and Precipitation in CAOs campaign (Principal Investigator: Trude Storelvmo) had similar objectives, using a Met Norway King Air aircraft. And the German Arctic Amplification campaign (AC3, PI Manfred Wendisch, also a co-Principal Investigator in COMBLE) was planning to deploy the DLR Polar 5/6 aircraft from Svalbard, mainly in the context of the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) campaign; they would have collected great upstream thermodynamic and wind profiles near the Arctic ice edge during CAOs. Ironically, March 2020 was an outstanding month for CAOs across the Norwegian Sea, which remains ice-free during the cold season, and thus is a hot spot for the CAO cloud regime. A cumulative total of 23 days of CAO conditions was observed at the AMF1 site during COMBLE, with an average M value (a measure of thermal instability driven by surface heat fluxes) of 3.9 K.

Acronyms and Abbreviations

2NFOV	narrow field of view zenith radiometer
AC^3	Arctic Amplification
ACIA	Arctic Climate Impact Assessment
ACSM	aerosol chemical speciation monitor
AERI	atmospheric emitted radiance interferometer
AGL	above ground level
AMF	ARM Mobile Facility
AOS	Aerosol Observing System
ARM	Atmospheric Radiation Measurement
ASR	Atmospheric System Research
AWS	automated weather station
BBSS	balloon-borne sounding system
BL	boundary layer
BLC	boundary-layer convection
CAO	cold-air outbreak
CEIL	ceilometer
CFAD	contoured frequency by altitude diagrams
COMBLE	Cold-Air Outbreaks in the Marine Boundary Layer Experiment
CRM	cloud-resolving model
CSPHOT	Cimel sunphotometer
CSU	Colorado State University
DL	Doppler lidar
ECOR	eddy correlation flux measurement system
GNDRAD	ground radiometers on stand for upwelling radiation
HTDMA	humidified tandem differential mobility analyzer
INP	ice-nucleating particle
IPCC	Intergovernmental Panel on Climate Change
IRT	infrared thermometer
KAZR	Ka-band ARM Zenith Radar
LDIS	laser disdrometer
LES	large-eddy simulation
MBL	marine boundary layer
MFRSR	multifilter rotating shadowband radiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MOSAiC	Multidisciplinary Drifting Observatory for the Study of Arctic Climate

MPL	micropulse lidar
MRR	MicroRain Radar
MWR-2C	microwave radiometer − 2-channel
MWR-3C	microwave radiometer − 3-channel
NSA	North Slope of Alaska
NWP	numerical weather prediction
ORG	optical rain gauge
PI	principal investigator
PWD	meteorological data (pressure, wind)
RWP	radar wind profiler
SACR	Scanning ARM Cloud Radar
SEBS	surface energy balance system
SKYRAD	sky radiometers on stand for downwelling radiation
TBRG	tipping bucket rain gauge
TSI	total sky imager
VAP	value-added product
WBRG	weighing bucket rain gauge
WMO	World Meteorological Organization

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1.0   Background

Climate models are the primary tool policy makers rely on to determine acceptable levels of greenhouse gases in the atmosphere as the Earth experiences global change, and to make informed decisions about infrastructure investment for future energy and resource needs. Hence performance evaluation and improvement of climate models is of paramount importance to better understand the role of Earth's biogeochemical systems (atmosphere, land, oceans, sea ice, subsurface) that ultimately control climate and to predict climate decades or centuries into the future.

Further, the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2013) identifies the response of clouds to both increased greenhouse gases and aerosol forcing as major uncertainties in climate models, especially related to the radiative forcing of the climate system. Reducing this uncertainty requires evaluation and improvement of not only climate models but also of large-eddy simulations (LES) and cloud-resolving models (CRMs) because results from such fine-resolution models are used to develop and test parameterizations of physical processes in climate models. Any advancement in climate models and their LES building blocks requires an understanding and accurate representation of the physical processes that, ultimately, depends on targeted observations.

One particular region where model improvement and targeted observations are needed is the Arctic. This region has experienced warming faster than the rest of the Earth (ACIA 2005, Serreze and Barry 2011), at a rate faster than predicted by climate models (Solomon et al. 2007). Several studies have suggested that cloud feedbacks (e.g., Vavrus 2004) are important contributors to arctic warming and may play a significant role in sea ice loss (e.g., Kay and Gettelman 2009). Further, Inoue et al. (2006) showed that large uncertainties remain in climate projections due to the inadequate treatment of aerosol-cloud-precipitation linkages.

A key to understanding and predicting the life cycle of arctic clouds, including mixed-phase convective clouds associated with cold air outbreaks (CAOs), lies in characterizing their cloud microphysical and macrophysical properties that impact their radiative properties and interact with atmospheric dynamics across all scales. Although some prior studies and measurement campaigns have analyzed the microphysical, macrophysical, and radiative properties of arctic clouds using in situ measurements and retrievals, observations have been limited to specific seasons and locations and have not thoroughly documented how cloud properties vary under the range of surface and meteorological conditions encountered in the Arctic. In particular, high-latitude convective boundary-layer clouds during CAOs over open water have not been studied systematically (Section 1.3). Thus, there is an urgent need to determine how cloud properties and formation mechanisms vary with surface, environmental, and aerosol conditions in the high-latitude marine boundary layer (MBL) during CAOs.

Clouds within the MBL have a larger radiative influence on the Earth than any other cloud type (Hartmann et al. 1992). MBL clouds are often convective, and cloud processes define the depth and properties of the MBL. Over mid- and high-latitude oceans off continents or the ice edge, boundary-layer convection (BLC) occurs when a cold air mass becomes exposed to a sufficient fetch of relatively warm open water, and transforms with increasing fetch in response to surface heat fluxes, constrained by the free tropospheric stability. Despite their common occurrence, our understanding of their properties, their role in energy and water cycles, and their treatment in climate models are arguably among the poorest of

all cloud types (Remillard and Tselioudis 2015). The surface latent and sensible heat fluxes in CAOs may be higher than anywhere else on Earth, often in excess of 500 W m^{-2} (Shapiro et al. 1987). Thus, even though CAO events are transient, they may have a profound impact on circulations in the atmosphere, where they may impact polar cyclogenesis (Terpstra and Spengler 2016), the intensity of baroclinic disturbances, and the location of the mid-latitude storm track. CAO events also affect ocean circulations: the heat loss they cause in the near-surface layers may be sufficiently strong in some areas for the surface waters to become negatively buoyant, sink to depth and form deep ocean water (Dickson et al. 1996, Spall and Pickart 2001). Changes in frequency and intensity of CAOs in a changing climate and changing arctic sea ice extent thus may have profound feedbacks on the climate system, e.g., on polar cyclogenesis (Zahn and von Storch 2010) and deep-water formation (Moore et al. 2015).

The depth, size, and linear/cellular organization of BLC are highly fetch-dependent and contingent on synoptic conditions, in particular, surface wind speed and temperature, and stability of the layer above the developing MBL. BLC involves interactions between surface fluxes, turbulence, clouds, and precipitation, as well as radiative processes. While many field campaigns and related modeling studies have explored the MBL in warmer climates, especially over subtropical oceans, numerical models (in particular, regional climate models) are far less constrained by observations in CAOs at high latitudes.

To improve our understanding of BLC associated with CAO events, and to develop parameterizations appropriate for climate models, observations are required to determine the environmental parameters that control their microphysical and macrophysical properties, and thus ultimately to determine how they change in response to global warming. Because low-level clouds are sensitive to sensible and latent heat fluxes from the ocean surface, co-located observations of cloud and ocean properties are needed to determine the ocean-atmosphere interactions affecting BLC. Aerosols are also believed to greatly influence CAO low-level clouds. Although some studies have shown how CAO low-level clouds vary in response to changes in the concentration and composition of aerosols (e.g., Lance et al. 2011, Jackson et al. 2012), these prior campaigns have concentrated on measurements near Barrow, Alaska in coastal regions, and have not had an adequate sample to determine how the aerosol effects vary with surface, meteorological, and aerosol characteristics. Dedicated data collection focusing on a specific cloud system that remains rather poorly documented will improve the representation of aerosol, clouds, radiation, and precipitation processes in numerical weather prediction (NWP) models and in regional and global climate models. CAOs also affect the climate system through oceanographic processes, in particular, by modulating surface heat and momentum fluxes and deep-water formation.

This is the broad motivation for the COMBLE (Cold-air Outbreaks in the Marine Boundary Layer Experiment) campaign, conducted successfully between 1 December 2019 and 31 May 2020 around the Norwegian Sea, to focus on convective clouds in the MBL during CAOs, as illustrated in Figure 1.

Figure 1.   Moderate Resolution Imaging Spectroradiometer (MODIS) visible image of a CAO event in the Norwegian Sea on 17 March 2019 (source: https://earthobservator.nasa.gov/).

COMBLE data will improve the representation of aerosol particles, clouds, radiation, precipitation, and boundary-layer processes in regional and global climate models. These data are sorely needed since MBL clouds represent a significant challenge to regional and global climate models, especially in high-latitude regions, as they generally are sub-grid-scale and fall in the gray zone where boundary-layer processes and convection are tightly coupled and cannot be parameterized independently. Mutual benefits are expected because COMBLE will coincide with several related efforts, in particular, MOSAiC.

2.0   Notable Events or Highlights

2.1   Instruments and Instrument Performance

The ARM crew was able to maintain robust operations for all 6 months at the AMF1 site (called ANX in COMBLE) and at Bjørnøya (Bear Island, called S2 in COMBLE), notwithstanding the COVID-19 pandemic. Met Norway assisted ARM in many aspects, ranging from site surveys to the operation of ARM instruments at Bjørnøya. The AMF1 instrument deployment at AMF1 is shown in Figure 2. Details
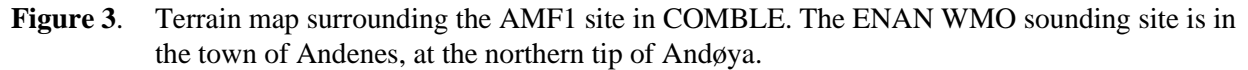
of the instruments can be found at the ARM Data Center,
https://www.arm.gov/research/campaigns/amf2020comble

Radiosonde data were collected every 6 hours from the AMF1 site, and every 3 hours (during CAOs only) from the ENAN site located in Andenes some 20 km to the NE (thanks to Met Norway personnel) (Figure 3). In addition, Met Norway operated a volume-scanning C-band radar called Trolltinde some 14 km from the AMF1 site, on a ~300-m-high hill (Figure 3). These data are available in the ARM Data Center.
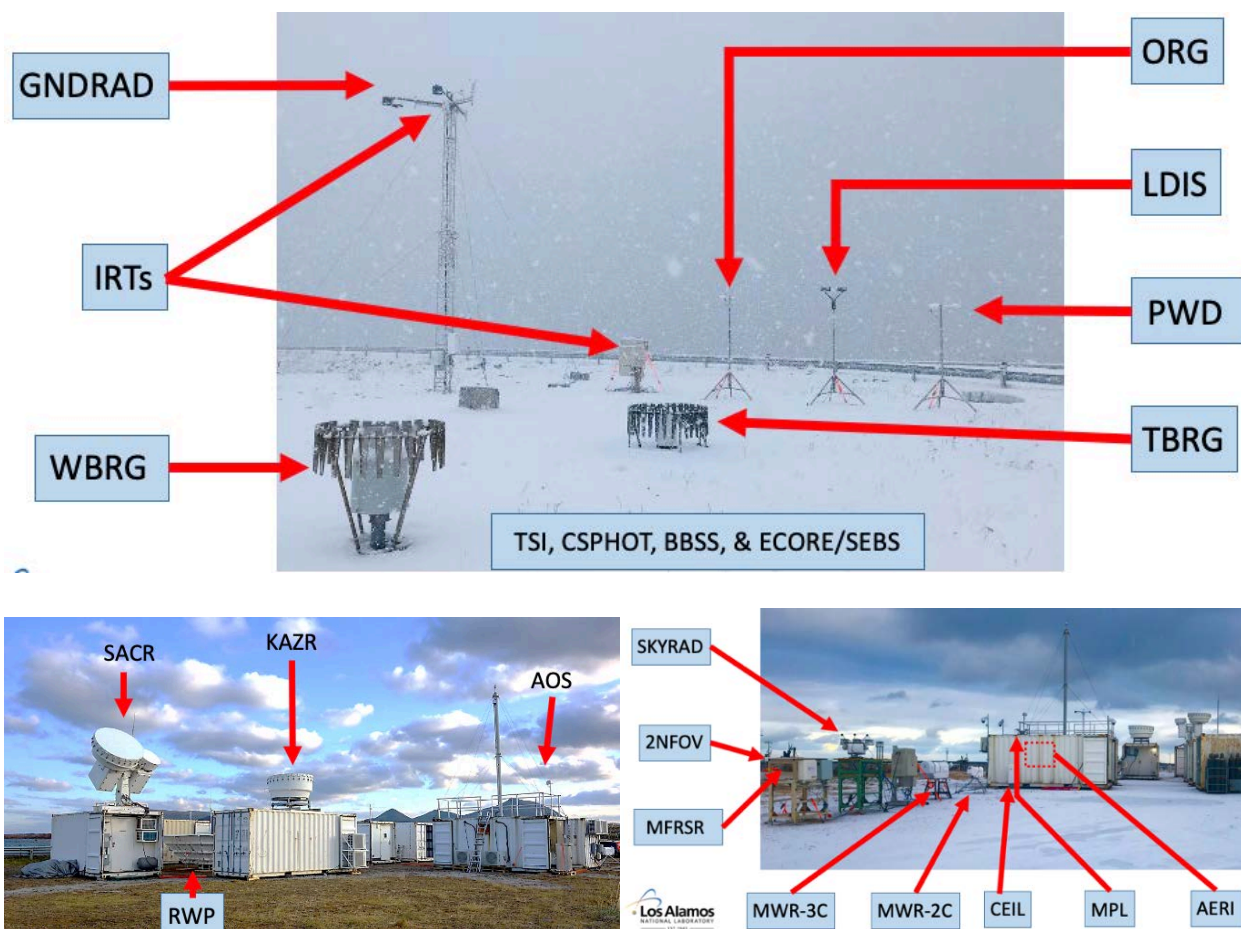
Figure 2.   Instruments at AMF1, located in Nordmela harbor, on Andøya, an island just off the northern Norwegian mainland (Figure 3).

Figure 3.   Terrain map surrounding the AMF1 site in COMBLE. The ENAN WMO sounding site is in the town of Andenes, at the northern tip of Andøya.

With the critical assistance of ARM technicians onsite, aerosol filter collections for subsequent measurements of immersion freezing ice nucleating particle (INP) concentrations as a function of temperature were made over periods of 6 to 74 hours (average 34 h and 42 m³ filtered), with periods tailored to integrate CAO or flanking periods of non-CAO air (DeMott and Hill 2020, in preparation). Open-faced filters were sampled at a height of 4 m AGL on the Aerosol Observing System (AOS) trailer (6 m below its inlet, visible under a rain "hat" in Figure 2). A total of 68 filters (4 blanks) were collected over the COMBLE deployment, stored at -20°C following sampling, and returned frozen in a dry nitrogen shipper for processing at Colorado State University (CSU) at the end of the campaign. Processing of re-suspended particles in the CSU ice spectrometer provided INP concentrations from 0 to -29°C for 63 sample periods. Additional processes to identify INP compositional contributions as biological, organic, and inorganic were performed on roughly 40% of the samples. The data set is described in DeMott and Hill (2020, in preparation), and data have been submitted to the ARM Data Center.

Three instrument issues occurred at the AMF1 site:

- Micropulse lidar (MPL) – transferred to MOSAiC early in campaign

- Humidified tandem differential mobility analyzer (HTDMA) and aerosol chemical speciation monitor (ACSM) – down for much of campaign

- Radar wind profiler (RWP) – down for several weeks.

The AMF1 instrument deployment at Bjørnøya is shown in Figure 4. In addition to the ARM data, there are 3-hourly radiosondes by Met Norway (World Meteorological Organization [WMO] site code: ENBJ) during CAOs only, although some of these did not materialize for a variety of reasons (technical and personnel-related). The University of Cologne collected MicroRain Radar (MRR) data during COMBLE from Bjørnøya, and these data are planned to be in the ARM Data Center soon (contact: Kerstin Ebell kebell@meteo.uni-koeln.de).

- DL
- CEIL
- MPL
- MWR-2C
- LDIS
- TSI
- ECORE/SEBS
- AWS
- BBSS
- MRR (U. Cologne)
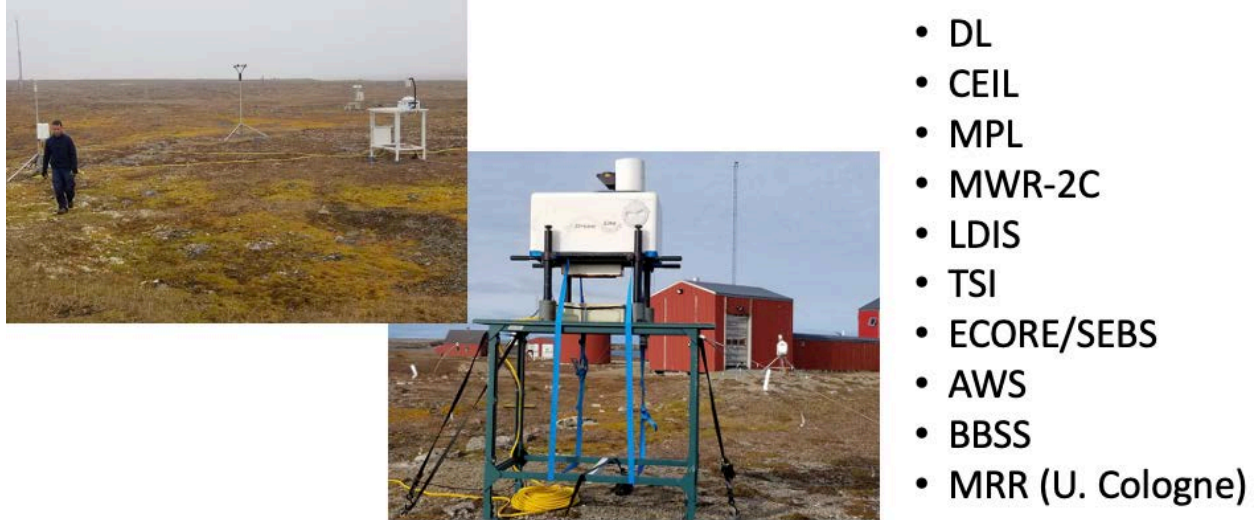
Figure 4.   Instruments at the site of the Met Norway station on the north side of Bjørnøya.

Two instrument issues occurred at Bjørnøya:

- MPL became encrusted in snow and ice; data loss for a few weeks, until it was moved.

- Microwave radiometer−2-channel (MWR−2C) had a broken component, which was repaired, notwithstanding the remote location.

2.2 Weather Conditions

A cumulative total of 23 days of CAO conditions was observed at the AMF1 site during COMBLE, with an average *M* value (a measure of thermal instability driven by surface heat fluxes) of 3.4 K. Here, CAO conditions are defined as:

1. *M*>0, where $M \equiv \theta_{SST} - \theta_{850\ hPa}$, and SST is the sea surface temperature about 10 km offshore the AMF1 site

2. Ka-band ARM Zenith Radar (KAZR) first echo top below 5.0 km (not enforced for now, because of frequent seeder-feeder situations)

3. surface wind speed >10 kts

4. surface wind direction between 250 and 30 degrees

5. continuity: short gaps (<1 hr) are skipped; minimum duration 1 hr

All conditions have to apply. Note that this definition does not take cloud microstructure into consideration.

The better CAO cases are listed in Table 1. These cases stand out in terms of their persistently high *M* value, their synoptic signature (with trajectories originating over the arctic sea ice), and their duration. Also, in all three cases, winds at ANX were rather strong, and the wind direction close to normal to the shore of Andoya.

Table 1.   The three best CAO cases at the AMF1 site. *M* is defined above.

Start time (yy/mm/dd zz)	End time (yy/mm/dd zz)	Duration (minutes)	Mean M [K]	Mean Wind Magnitude [m/s]	Mean Wind Direction [°]
20/02/04 15:47	20/02/06 13:04	2718	7.2	7.7	308
20/03/27 22:47	20/03/29 09:09	2063	6.6	8.0	314
20/03/12 18:30	20/03/14 02:09	1900	7.8	7.6	336

Sample satellite and radar images of two of the three cases listed in Table 1 is shown in Figure 5. Both cases reveal air trajectories originating at the ice edge in the northern Fram Strait. No MODIS imagery is available for the third case in early February because the Norwegian Sea was still largely in the polar night during Aqua/Aura overpasses.

The vertical structure of the CAO cloud regime is illustrated in Figure 6, for the 27-29 March 2020 case. Clouds clearly are convective, and they are remarkably deep, up to 4.5 km deep, much deeper than the traditionally defined MBL. Towards the end of this CAO, upper-level warm-frontal clouds overrun the shallow cold-airmass, gradually deepening and stifling the CAO.
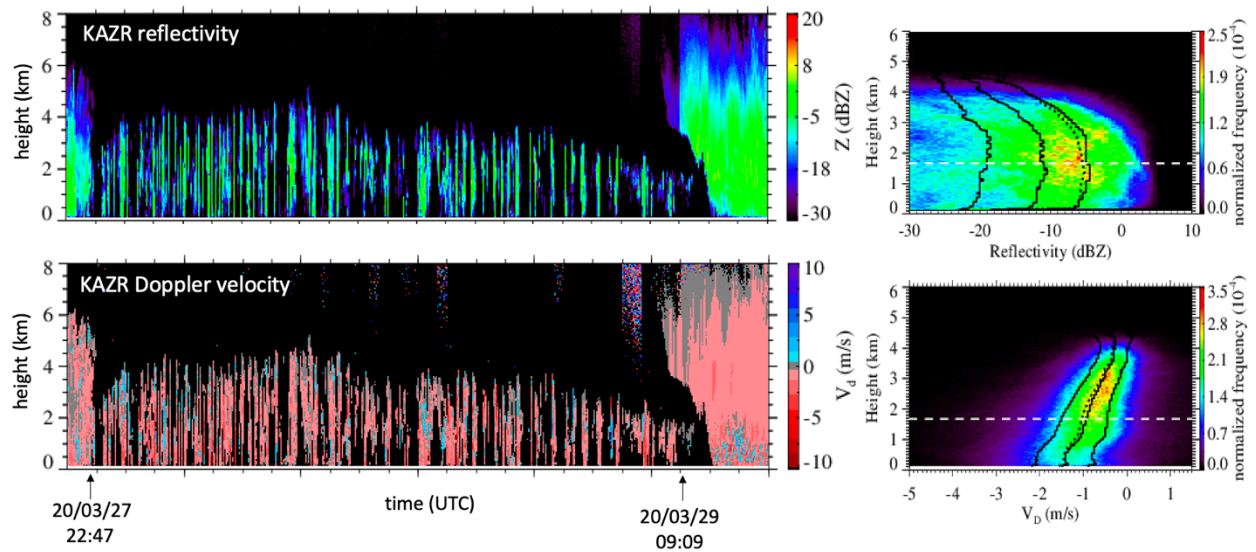

Satellite imagery & radar mosaic reflectivity
03/13/2020 0950 UTC

Radar reflectivity (dBZ)
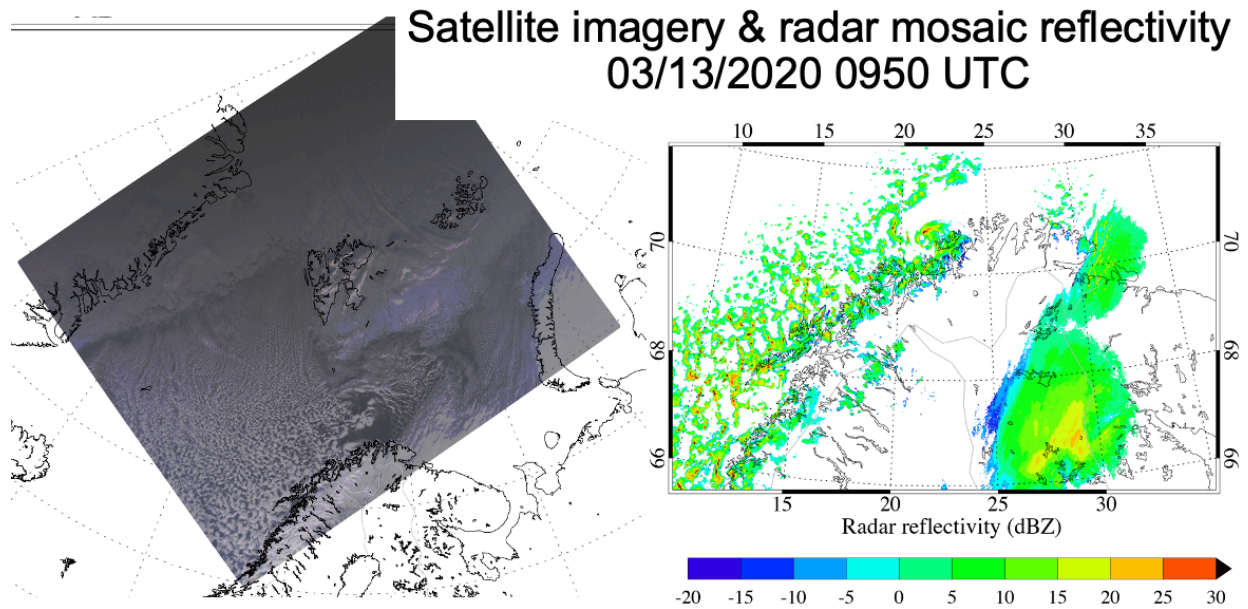
03/29/2020 0950 UTC
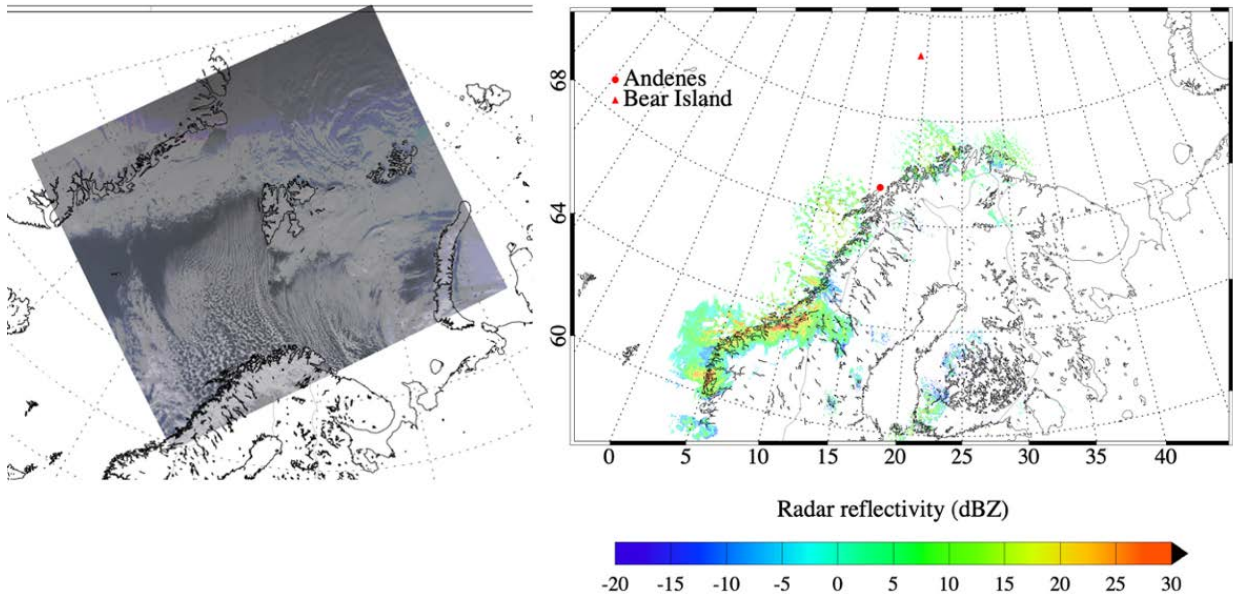
Figure 5.   (left) MODIS visible imagery (data source: https://earthobservatory.nasa.gov/) and (right) Met Norway radar mosaic (data source: https://thredds.met.no) for two of the three better CAOs in COMBLE.

Figure 6.   (left) KAZR reflectivity and Doppler velocity profiles for the CAO of 27-29 March 2020. (right) Corresponding CFADs (contoured frequency by altitude diagrams). The solid black lines are the 25/50/75 percentiles, and the dotted line is the average.

The red periods in Figure 7 show all CAO periods, as defined above. (Data were collected continuously, so non-CAO periods can be studied as well.) CAO conditions were more common on Bjørnøya, and the thermal instability higher, as expected from climatology. We are waiting for the interpsonde value-added produce (VAP) to finalize the CAO periods on Bjørnøya.
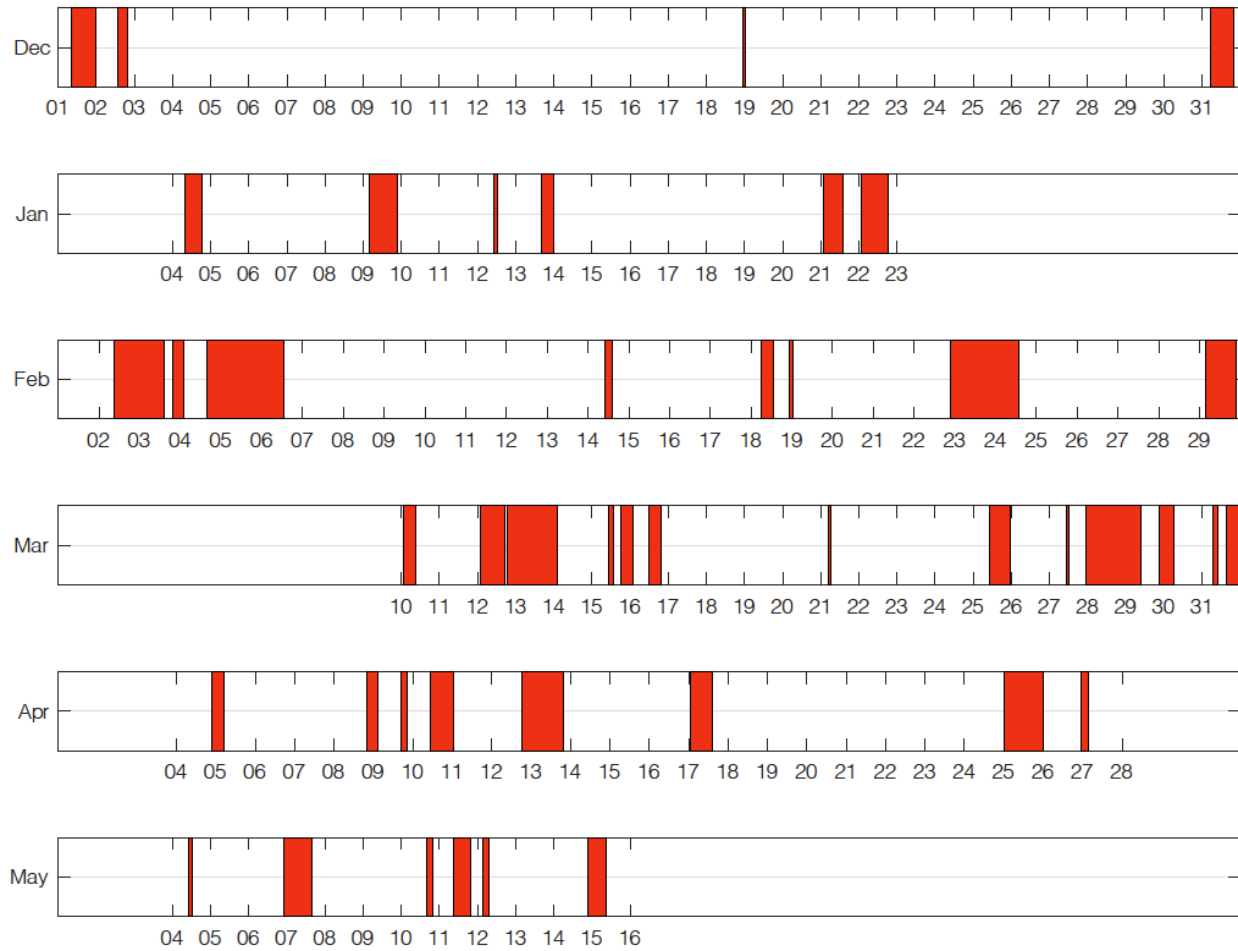
Figure 7.   CAO periods at the AMF1 site during the COMBLE campaign, between 1 December 2019 and 31 May 2020.

3.0   Some Preliminary Results

Altogether, COMBLE was a great success. A wide range of thermal instability, wind speed, cloud top height, and precipitation intensities were observed at both sites during CAOs in COMBLE. Figures 7-14 show environmental conditions and basic cloud properties during the CAO periods at the AMF1 site. The mean *M* value was 3.9 K at the AMF1 site (Figure 8). The surface winds were between westerly and northerly, mainly ~320° (NW), which is roughly normal to the Andøya coastline (Figure 9). The surface temperature generally was between 0-5°C (Figure 11), and the CAO clouds generally produced light precipitation (Figure 15).

Some of these results are preliminary, for instance, a better definition of MBL depth is possible (Figure 12).

We are planning to do the same analysis for Bjørnøya, once we can define CAO conditions there (for which we need interpsonde data. The AMF1 site was located at rather great fetch (about 1000-1200 km)

from the arctic ice edge, at Nordmela harbor, on the island of Andøya just off the coast of northern Scandinavia). The Bear Island site was located some 500 km closer to the ice edge. In March 2020, the marginal ice zone briefly reached this island, as arctic ice was advected from the east side of Svalbard.

Any study of the CAO cloud regime at the AMF1 site should take into account the possible influence of downwind topography. Within a few km, terrain ~300 m high is present, on the island of Andøya. Further downwind, over a distance of ~50 km, the Scandinavian highlands ~1200 m high are present with deep fjords intersecting the foreland (Figure 3). This terrain impacts synoptic, mesoscale, and local circulations, and thus cloud and precipitation.

This influence is suggested in the KAZR reflectivity profiles. In many cases precipitation fell continuously from upper cloud layers into the boundary-layer (BL) clouds: therefore the BL cloud top height could not be readily defined. This appears more prevalent in COMBLE than at ARM's North Slope of Alaska (NSA) site, for instance, because the immediate hinterland of the AMF1 site in COMBLE is mountainous (versus flat at the NSA site). Upslope flow over this downwind terrain presumably caused ascent of free-tropospheric layers, resulting in sometimes deep precipitation profiles above the AMF1 site, hiding the BL clouds. We plan to use KAZR Doppler velocity and spectral width data to identify these cases of upper-level clouds feeding shallow clouds.
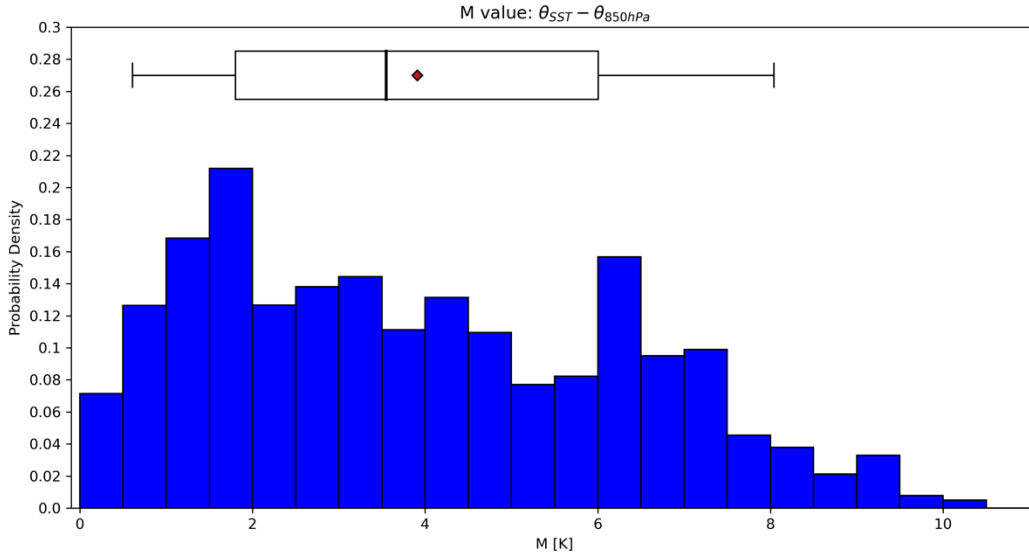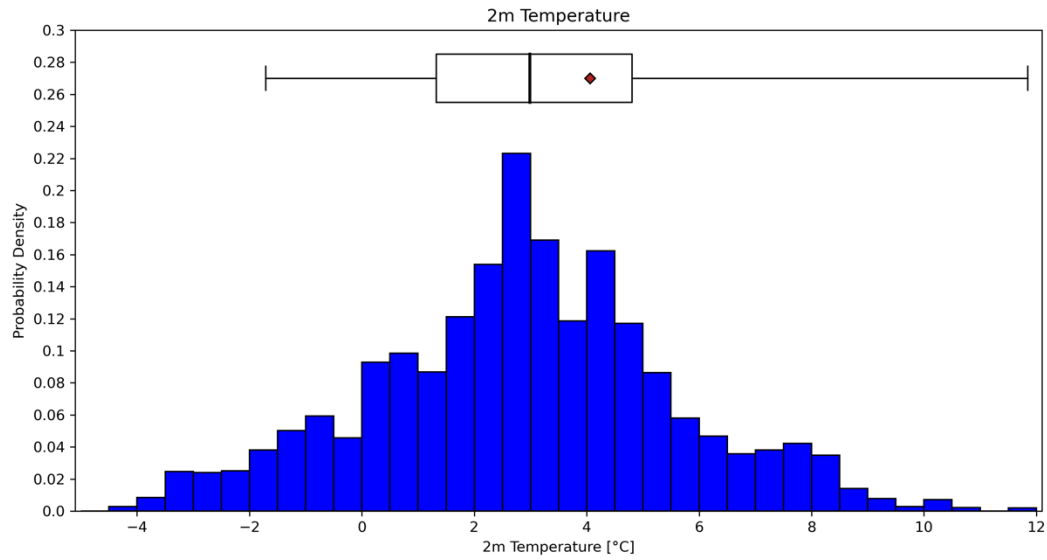

Figure 8. Distribution of *M* values, at the AMF1 site during CAO periods identified in Figure 7.
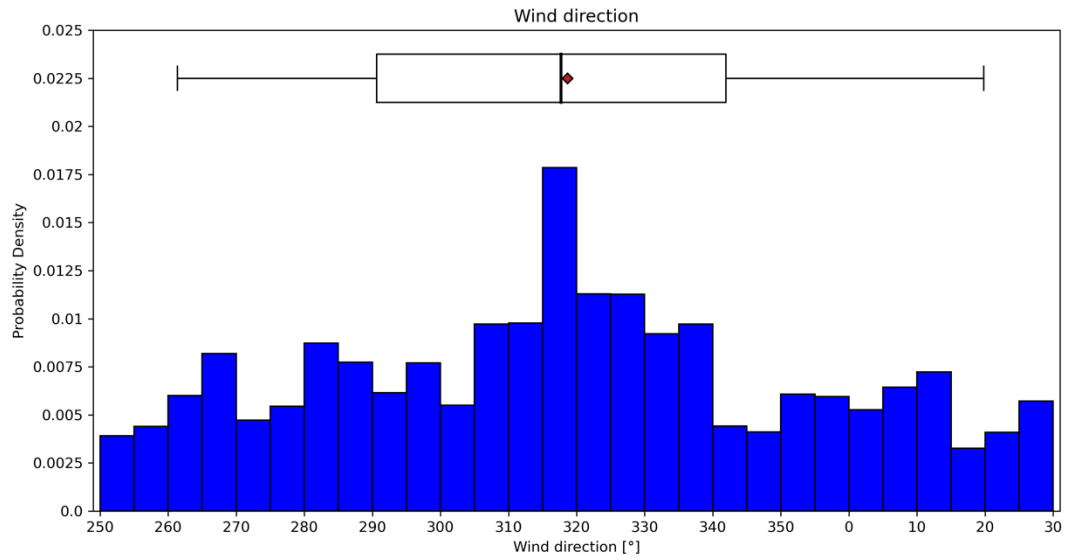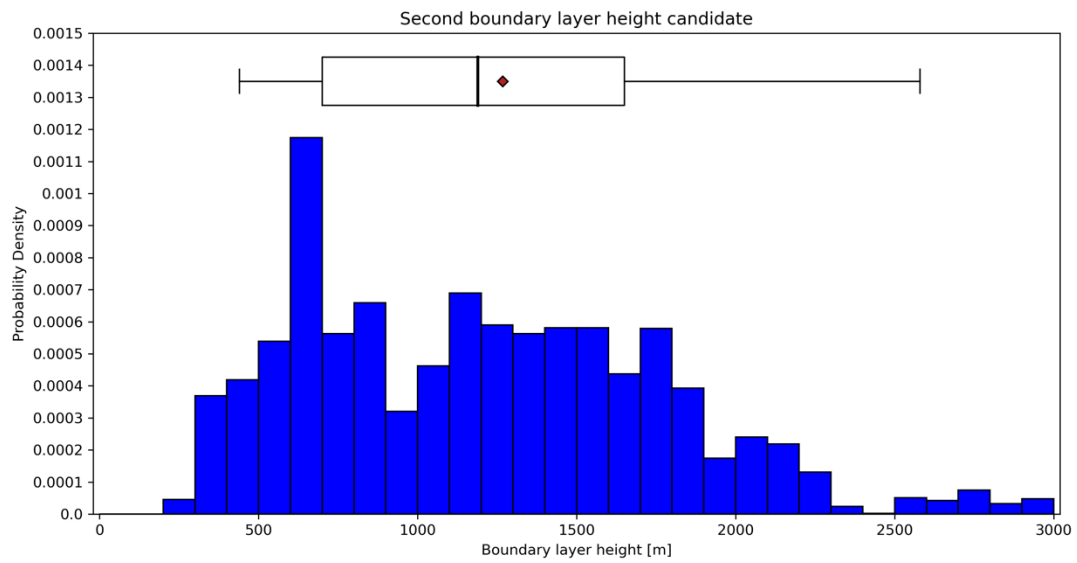
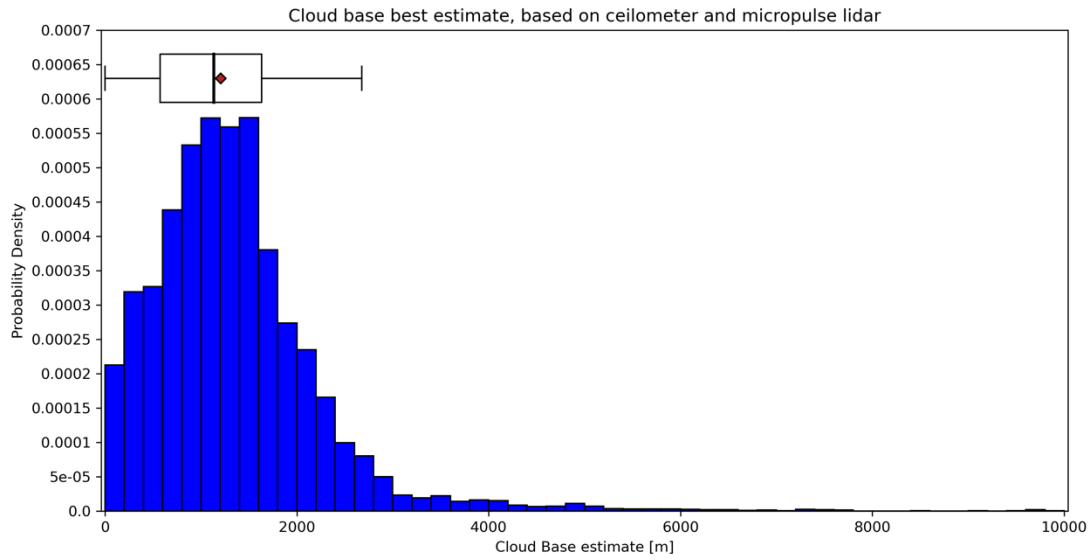**Figure 9**. Surface wind direction, at the AMF1 site during CAO periods identified in Figure 7.
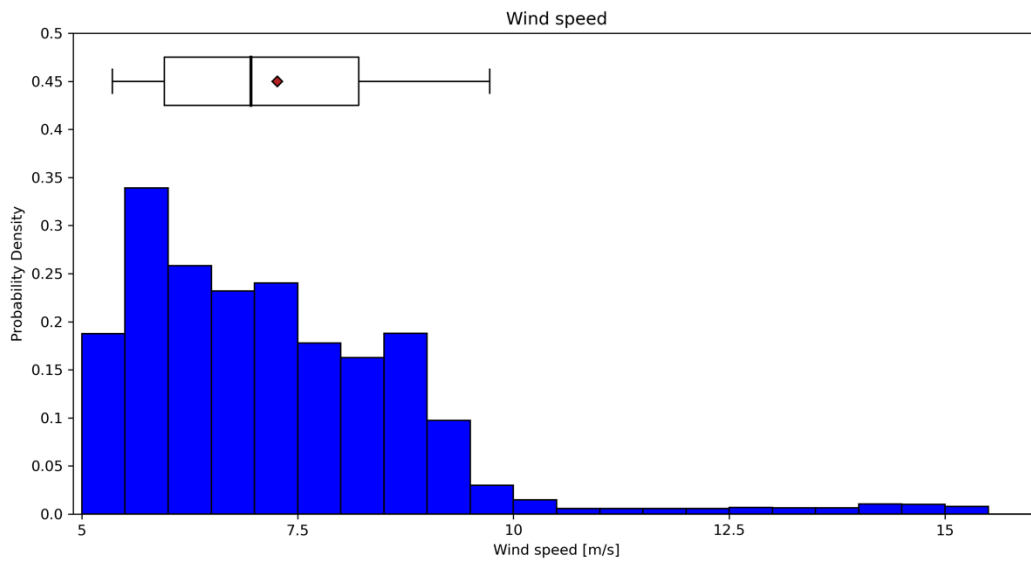
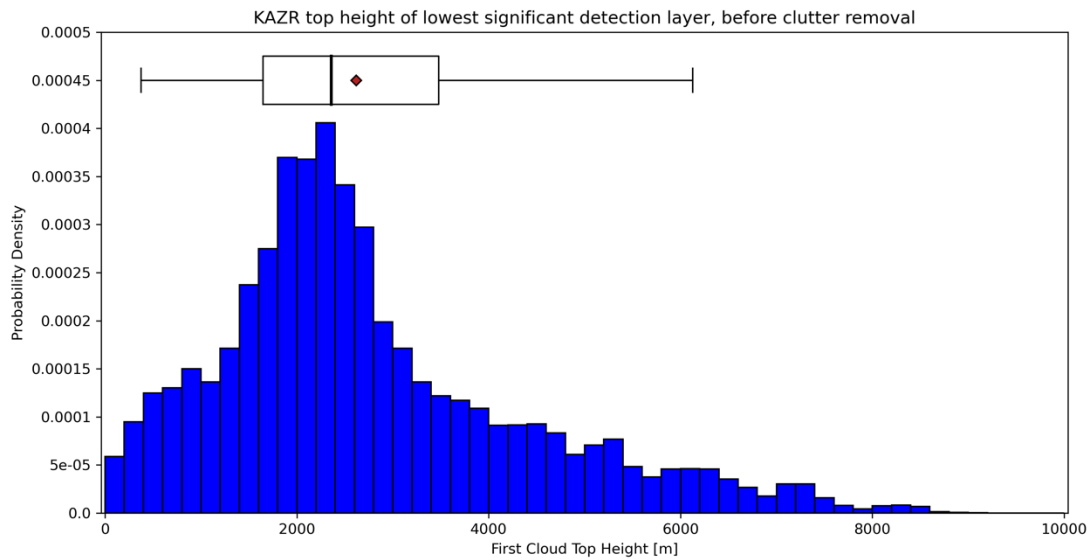**Figure 10**. Surface wind speed, at the AMF1 site during CAO periods identified in Figure 7.

Figure 11. Surface temperature, at the AMF1 site during CAO periods identified in Figure 7.


Figure 12. Best-estimate boundary-layer (mixed-layer) depth, at the AMF1 site during CAO periods identified in Figure 7.

Figure 13. Cloud base estimated from ceilometer and/or micropulse lidar, at the AMF1 site during CAO periods identified in Figure 7.

Figure 14. Best-estimate echo top height of lowest cloud layer, at the AMF1 site during CAO periods identified in Figure 7.
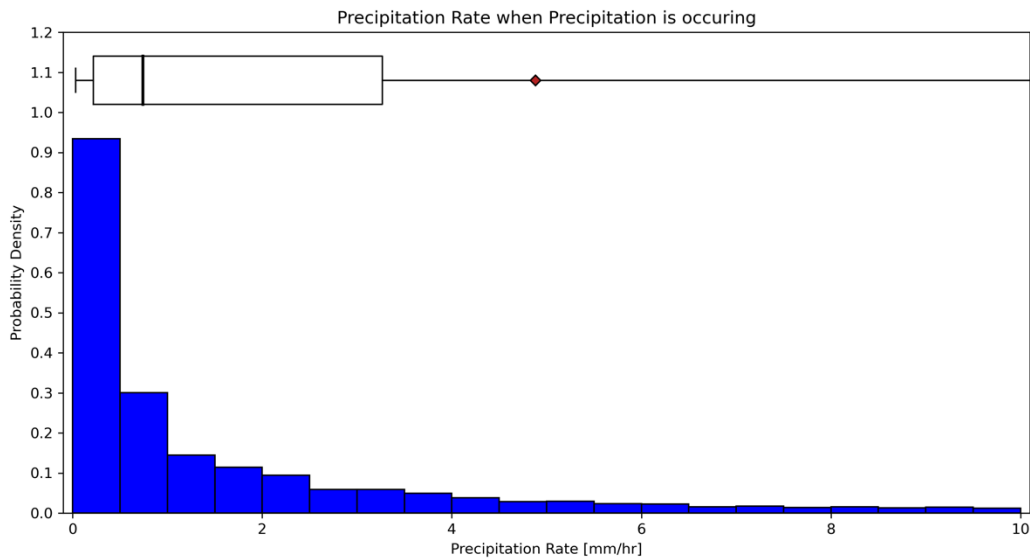
Figure 15. Precipitation rate, at the AMF1 site during CAO periods identified in Figure 7.

4.0 Public Outreach

The COMBLE campaign was conducted at a remote location, with no principal investigator (PI) presence at the site, hence there was no open house or other outreach to local schools or universities. There were several news coverages and blogs about COMBLE, archived at the ARM website:
https://www.arm.gov/news-events/search?q=comble

5.0 COMBLE Publications

5.1 Journal Article Manuscripts

At this time, no journal articles focused on COMBLE have been published, but several are in preparation.

5.2 Meeting Abstracts/Presentations/Posters

Dedicated sessions on COMBLE were held at the ARM/Atmospheric System Research (ASR) Joint PI meetings in 2019 and 2020, as well as presentations focused on or mentioning COMBLE at the 2020 American Geophysical Union Fall meeting, including Geerts et al. (2020).

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