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Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE) Science Implementation Plan

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Executive Summary

Boreal regions have experienced warming faster than the rest of the Earth, and the arctic ice cover has declined at a rate faster than predicted by most climate models. Uncertainties in climate projections for this region are large, in part due to the lack of observational guidance to constrain the treatment of aerosol-cloud-precipitation linkages in climate models. To remedy this shortfall, field campaigns have been conducted to collect integrated, comprehensive measurements under specific atmospheric regimes. While considerable efforts have been devoted to subtropical marine boundary-layer clouds, as well as to clouds in the stable arctic environment, very few targeted observations exist of convective boundary-layer clouds that form over open water when cold airmasses are advected off ice-covered regions or boreal continents.

There is an urgent need to shed light on the dynamics and microphysical properties of clouds and precipitation in the high-latitude marine boundary layer during cold-air outbreaks. Despite the common occurrence of linear and cellular cloud patterns that typify cold-air outbreaks, little is known about the properties of these clouds; how they vary with surface, environmental, and aerosol conditions; the role of cold-air outbreaks in the global atmospheric and ocean circulation; and the accuracy of the treatment of this atmospheric regime in climate models.

Thus, we proposed to conduct the *Cold-Air Outbreaks in the Marine Boundary Layer Experiment* (COMBLE), to focus on marine boundary-layer clouds during cold-air outbreaks. COMBLE will deploy the first ARM Mobile Facility (AMF1) and an AMF “satellite” station in the far North Atlantic in January–May 2020. COMBLE will take advantage of the synergy with several coincident campaigns, notably MOSAIC, which will characterize the source airmasses of cold-air outbreaks over the arctic ice, and $(AC)^3$, which will operate several aircraft between northern Scandinavia and the MOSAIC deployment to document evolution of these airmasses. COMBLE and its sister campaigns will compose a four-member array of supersites between northern Scandinavia and the Arctic, each with profiling and in situ cloud, precipitation, radiation, and aerosol measurements.

COMBLE will be guided by six science themes. The first five deal with boundary-layer convection in cold-air outbreaks: (1) the fetch-dependent mesoscale organization of clouds and precipitation, including linear and cellular convection; (2) surface heat and momentum fluxes and vertical profiles of temperature, humidity, wind, and turbulence; (3) vertical structure of clouds and precipitation; (4) the sources and sinks of aerosol, including ice-nucleating particles, and the role of cloud-active aerosol on cloud processes and radiative fluxes; and (5) the influence of these four themes on polar cyclogenesis and polar low vertical structure. The overarching sixth theme is that COMBLE will provide *integrated data sets of dynamical, thermodynamic, and cloud microphysical characteristics of marine boundary-layer convection in cold-air outbreaks, including cloud and aerosol properties, that will enable constraining high-resolution numerical simulations, developing process-level understanding, and, subsequently, evaluating and improving representations of shallow convection in weather and climate models.*

Acronyms and Abbreviations

$(AC)^3$	Arctic Amplification: Climate Relevant Atmospheric and Surface Processes, and Feedback Mechanisms
ACIA	Arctic Climate Impact Assessment
ACSM	aerosol chemical speciation monitor
AERI	atmospheric emitted radiance interferometer
AMF	ARM Mobile Facility
AOS	aerosol observing system
ARM	Atmospheric Radiation Measurement
AWI	Alfred Wegner Institute
BER	Biological and Environmental Research
BL	boundary layer
BLC	boundary-layer convection
CAO	cold-air outbreak
CCN	cloud condensation nuclei
CEIL	ceilometer
CESD	Climate and Environmental Sciences Division
CMIP5	Coupled Model Intercomparison Project phase 5
COMBLE	Cold-Air Outbreaks in the Marine Boundary Layer Experiment
CPC	condensation particle counter
CRM	cloud-resolving model
CSU	Colorado State University
CW-RHI	crosswind range-height indicator
DOE	U.S. Department of Energy
ECOR	eddy correlation flux measurement system
EMSL	Environmental Molecular Sciences Laboratory
FOV	field of view
GCM	general circulation model
GPM	Global Precipitation Measurement
HS-RSI	hemispherical sky range-height indicator
ICON	Icosahedral Nonhydrostatic Weather and Climate Model
INP	ice-nucleating particle
IOP	intensive operational period
IP	internet protocol
IPCC	Intergovernmental Panel on Climate Change
IR	infrared

ISR	Instrument Support Request
KASACR	Ka-band Scanning ARM Cloud Radar
KAZR	Ka-band ARM Zenith Radar
LDIS	laser disdrometer
LES	large-eddy simulation
LW	longwave
MBL	marine boundary layer
Mbps	Megabits per second
MET	surface meteorological instrumentation
MFRSR	multi-filter rotating shadowband radiometer
MICRE	Macquarie Island Cloud and Radiation Experiment
MOSAIC	Multidisciplinary Drifting Observatory for the Study of Arctic Climate
MPL	micropulse lidar
MRR	micro-rain radar
MSR	micro-snow radar
MWR	microwave radiometer
MWRP	microwave radiometer profiler
NWP	numerical weather prediction
OPC	optical particle counter
OPS	optical particle sizer
PI	principle investigator
PPI	plan position indicator
PSAP	particle soot absorption photometer
QC	quality control
RH	relative humidity
RWP	radar wind profiler
SW	shortwave
TKE	total kinetic energy
TSI	total sky imager
VPT	vertically pointing type
WMO	World Meteorological Organization
WSACR	W-band Scanning ARM Cloud Radar

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1.0 Introduction

Climate models are the primary tool policymakers 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 which, 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 there are large uncertainties 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 (Rémillard 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 to ultimately 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.

Figure 1. MODIS visible image of a CAO event in the Norwegian Sea on 17 March, 2016 (source: https://earthobservatory.nasa.gov/).

Thus, we proposed a dedicated data collection campaign, COMBLE (Cold-Air Outbreaks in the Marine Boundary Layer Experiment), to focus on convective clouds in the MBL during CAOs, as illustrated in Figure 1. COMBLE 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 as COMBLE will coincide with several related efforts, in particular MOSAIC.

The U.S. Department of Energy (DOE)'s ARM Decadal Vision (2014) calls for the deployment of the ARM Mobile Facilities (AMFs) in regions where measurements are most needed for climate research, such as the Arctic. The Arctic is subject to an amplified response to global warming mainly due to its negative radiation balance resulting in a higher surface temperature increase to offset the same radiative forcing (Pithan and Mauritsen 2014). As high as a 12 K increase of the annual arctic mean near-surface temperature by 2100 has been predicted by the Coupled Model Intercomparison Project phase 5 (CMIP5) simulations in the RCP8.5 high-emission scenario (Koenigk et al. 2013), in part due to the ice-albedo feedback over the Arctic Ocean, although the magnitude of this feedback mechanism strongly depends on Arctic BL cloud extent and albedo. The COMBLE data will lead to an improvement in the representation of shallow, precipitating convection in a hierarchy of models, from LES to global climate models, through the evaluation and improvement of shallow convection and boundary-layer parameterizations.

2.0 Objectives

COMBLE will provide AMF-based in situ and remote-sensing observations. At the same time, airborne and ground-based observational campaigns already funded or planned in the context of COMBLE (detailed in Section 6) will link the AMF observations at sites well downstream of the ice edge to upstream conditions. The main objective for the planned deployment of the AMF, with accompanying measurements as detailed below, is to quantify the properties of BLC clouds and air mass transformation in CAOs over open water. Specifically, COMBLE aims to:

1. describe the *fetch-dependent mesoscale organization* of clouds, precipitation, and radiation in 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 BLC;
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. describe the importance of CAOs for the development of mesoscale/synoptic baroclinic disturbances, especially *polar lows*;
6. 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 BLC, and, subsequently, evaluating and improving representations of shallow convection in CAOs in weather and climate models.

3.0 Deployment Sites

Bear Island (Bjørnøya) is 200–500 km downwind of the ice edge, depending on wind direction and seasonal ice dynamics (Figure 2). It is ideally located between the northern Norwegian coast and Svalbard. This island is not equipped to host AMF1 (as it lacks a dock), but lightweight ARM sensors that do not require the AMF sea containers can be deployed. The set of ARM sensor systems requested (Table 4) is similar to that deployed during the Macquarie Island Cloud and Radiation Experiment (MICRE) in the Southern Ocean. Bear Island is manned by Meteo Norway. The island hosts a weather station and housing for weather service personnel. Meteo Norway will launch four radiosondes per day from this site. Meteo Norway will launch additional ARM radiosondes during COMBLE intensive operational periods (IOPs). ARM's collaboration with Meteo Norway will be essential for the installation and operation of ARM sensors.

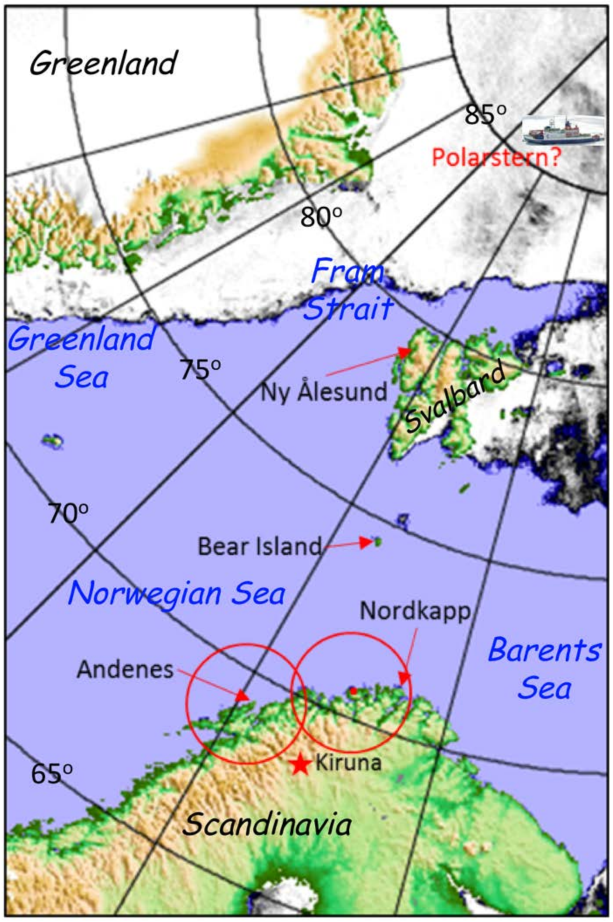

Figure 2. Map of northern Scandinavia and Svalbard, showing sea ice extent on 1 March, 2016. The red circles denote 100-km range rings around operational C-band radars. Ice site: *Polarstern* MOSAIC with AMF2, including radiosondes. Northern Site—Ny-Ålesund: Operational radiosondes, several profiling radar systems, and enhanced observations as part of the (AC)^3 project. Central site—Bear Island (Bjørnøya): Manned weather station (Meteo Norway), Radiosondes (released by Meteo Norway), user-provided profiling Ka-band radars (U. of Colorado), and ARM request—radiosondes, plus a series of lightweight ARM probes. Southern site—Andenes: operational radiosondes, C-band operational radar network, airport and logistics support, and ARM request—AMF1, aerosol observing system (AOS), radiosondes, and INP.

Andenes is 600-900 km downwind of the ice edge, depending on wind direction and seasonal ice dynamics (Figure 2). It is the preferred site for AMF1 and the AOS (Table 3).

4.0 Priority of Instruments for the Five Science Themes

All ARM instruments requested for COMBLE are “essential” for at least one science objective at both locations (Tables 1 and 2). A separate document below called “ARM resources requested” details the instruments, as well as practical aspects of deployment and operation.

Table 1. Justification of the AMF1 and AOS instruments in terms of the five science objectives. The number 1 indicates "essential"; 2 means "useful", and - means "not needed".

Andenes	**KASACR, WSACR, KAZR**	**AERI, MWR, radiosondes**	**MPL, TSI, LDIS**	**(ECOR), MET**	**AOS, INP**
1. Mesoscale structure	1	1	2	2	-
2. Surface fluxes and vertical structure	1	1	2	1	2
3. Clouds and precipitation	1	1	1	2	2
Cloud-active aerosol	2	2	1	2	1
Polar lows	1	1	2	2	-

Table 2. Justification of the AMF satellite in terms of the five science objectives.

Bear Island	**MWR, radiosondes**	**MPL, CEIL, TSI**	**ECOR, MET, MFRSR, photometer**	**LDIS**
1. Mesocale structure	1	2	2	2
2. Surface fluxes and vertical structure	1	1	1	-
3. Clouds and precipitation	1	1	1	1
4. Cloud-active aerosol	2	1	2	2
5. Polar lows	1	2	2	2

5.0 Traceability Matrix

A matrix that relates science objectives/hypotheses in COMBLE to measurement, instrument, and functional requirements is given in Table 3 below.

Table 3. Science traceability matrix.

Science objectives	Measurement requirement	Instrument requirement	Functional requirement
1. Mesoscale organization	*Horizontal* distributions of cloud, precipitation, kinematic, and thermodynamic variables	Scanning radar (KASACR, WSACR, Meteo Norway radars); time-height transects (KAZR, AERI, MWRP, MPL, RWP); spaceborne probes (GPM Ka/Ku radars, EarthCare radar/lidar, etc.)	KASACR and WSACR need good low-level view into the wind
2. Surface fluxes and vertical structure	Surface energy balance over water, incl. radiances, profiles of thermodynamic variables, humidity, wind, TKE	ECOR, MET, MFRSR, photometer; KASACR, WSACR, KAZR, AERI, MWRP, MPL, radiosondes	ECOR to be located close to shore; radiosondes every 3 hrs during CAO conditions, which may occur 24/7
3. Clouds and precipitation	Vertical distributions of vertical velocity, liquid water and ice mass, droplet and ice particle size distributions	KASACR, WSACR, KAZR, AERI, MWRP, MPL, LDIS	Accurate radar calibration of Z and V for dual-frequency techniques, fallspeed and vertical air motion estimation
Cloud-active aerosol	Aerosol size distribution INP concentration; mineral vs organic; radiative properties	CCN-200, CPC, nephelometer, INP filter	Minimize impact of local anthropogenic sources (harbor activities)
Polar lows	Horizontal and vertical structure of cloud, precipitation, kinematic, and thermodynamic variables	Scanning radar, time-height transects, and spaceborne probes, as for (1) above	KASACR and WSACR need good low-level view; accurate radar calibration
Model evaluation/ development	All of the above	All of the above	Synthesize data into model-meaningful variables in a time/space grid

6.0 Synergies with Related Field Work

6.1 Collaboration with Meteo Norway

The Norske Meteorologisk Institutt (Meteo Norway, http://met.no) is supporting COMBLE in several ways (Appendix 1). The main motivation for Meteo Norway is that the study of CAO events will improve weather forecasting. These multi-day events can bring snow to populated areas and are important for aviation forecasts (e.g., visibility, icing conditions). Meteo Norway has committed to assist with the deployment and operation of ARM and user-provided instruments on Bear Island, including the release of ARM radiosondes during CAOs, as long as the launch times comply with crew duty limitations. Meteo Norway routinely releases twice-daily radiosondes from Andenes (autosonde). We request that ARM releases additional radiosondes during CAOs, from the ARM site. Meteo Norway operates a network of 11 C-band weather radars along the entire Norwegian coast. Data from these radars are publicly available in near-real time.

Meteo Norway will also assist in forecasting to decide on an enhanced radiosonde release schedule during CAOs. They run two operational NWP models, AROME-MetCoOp and AROME-Arctic. AROME-MetCoOp is developed and operated jointly by Sweden and Norway. AROME-Arctic is focused on North Norway, Svalbard, and the Norwegian, Greenland, and Barents seas. Both operational models are convection permitting with 2.5-km horizontal resolution, and MetCoOp is an ensemble prediction system. Full model output data will be available in real time to COMBLE (and to the public). Plans for model output archiving have been discussed but are not final.

6.2 The Arctic Amplification Project $(AC)^3$

The Ny-Ålesund site will be enhanced with additional sensor systems as part of the Arctic Amplification project “$(AC)^3$” (ArctiC Amplification: Climate Relevant Atmospheric and SurfaCe Processes, and Feedback Mechanisms) (http://ac3-tr.de/). At this time, the first phase of $(AC)^3$ is funded through 2019, and a proposal for Phase II will be submitted in due time.

As part of $(AC)^3$, two lower-altitude, shorter-range aircraft, **Polar 5** and **Polar 6**, will be based at Longyearbyen (Svalbard) for flights over the Norwegian Sea and Fram Strait during dedicated periods that overlap with the ARM deployment, specifically in April and May, 2020 (PI: Christof Lüpkes).

Several $(AC)^3$-funded PIs are listed as COMBLE collaborators. The scientific interests and contributions from these $(AC)^3$ PIs to COMBLE are twofold: (a) observe cloud evolution during cold-air outbreaks (CAO), and (b) test the ability of atmospheric dynamical models of different complexity to represent the cloud development during CAO. They will perform aircraft observations (using the Polar 5 and 6) along the major trajectory of CAOs to link the local ARM measurements and the Lagrangian cloud evolution. In particular, they are interested in observing the transformation of microphysical cloud parameters (size and number concentration of droplets/ice crystals, liquid water and ice water content) during the lifetime of the clouds. For this purpose, we will derive these cloud parameters using synergistic measurements from airborne active (radar, lidar), passive (microwave radiometers, reflected solar spectral radiances), and in situ measurements. In addition to turbulent fluxes of energy and momentum, radiative fluxes will be measured above the clouds and combined with respective ground-based ARM data to derive the cloud radiative energy budget and to quantify the solar heating and terrestrial cooling effects of the clouds, which will be reproduced by respective radiative transfer simulations. The measurements will be compared to the output of a hierarchy of atmospheric dynamical models (from local LES to global Icosahedral Nonhydrostatic Weather and Climate Model [ICON]).

6.3 INP Measurements at Ny-Ålesund

Yutaka Tobo of the Japanese National Institute of Polar Research has led several campaigns to measure INP concentrations on Mt. Zeppelin (474 m) just above Ny-Ålesund. One of the techniques he now uses involves filter-based collection of immersion freezing measurement. This technique is essentially the same as that by Paul DeMott at Andenes (Section 7). Dr. Tobo is funded to make these measurements at Ny-Ålesund in January–April, 2020, to coincide with COMBLE. Thus, these data will describe upstream conditions that can be compared directly to the planned INP measurements in Andenes, on the downstream side. Dr. Tobo will also measure aerosol size distributions at the same site during COMBLE, using an optical particle counter (OPC) and an optical particle sizer (OPS), to focus on coarse particles (0.3 to 10 um), complementing AOS measurements downstream.

7.0 Instruments at Andenes

7.1 AMF1

A site survey was conducted by Kim Nitschke and the lead PI in June 2018. Several potential sites were identified for the AMF1 near Andenes, Norway, for the duration of COMBLE (1 January–31 May, 2020).

The instrument list is shown in Table 4. The ECOR deployment is listed at lower priority because the one on Bear Island has a higher priority. All other instruments are considered top priority, except the AOS, which contains probes of medium priority (Table 5).

Table 4. Priority table for the AMF1 instruments at Andenes. Priority #1 is "essential"; Priority #2 is "useful".

Instrument	Measurement	Priority
KASACR and WSACR (scanning)	35 and 95 GHz reflectivity, Doppler velocity, Doppler spectrum	1
KAZR (profiling)	35 GHz reflectivity, Doppler velocity	1
AERI and MWRP	Temperature and humidity profiles	1
MPL (profiling)	Backscatter power	1
TSI	Cloud fraction	1
LDIS	Hydrometeor size distribution, fallspeed	1
MET	Surface meteorology, precipitation	1
RWP (1290 MHz)	Wind profiles (>400 m height)	1
Doppler lidar	Wind profiles (0-400 m)	1
ECOR	Eddy correlation surface fluxes	2
AOS	Aerosol sizing and chemistry, gas chemistry	1-2
Radiosondes (120 total)	T, q, wind profiles	1

Radar scan strategy. The only scanning radar requested with the AMF1is the Ka/WSACR system (Kollias et al. 2014a, b). The proposed scan strategy includes a hemispherical sky range-height indicator (HS-RHI) scan (Kollias et al. 2014a) followed by 2-3 low-level plan position indicators (PPIs) covering a 180° azimuth sector with maximum range of 40 km to help capture the low-level clouds. The combined HS-RHI and PPI scan requires 5-6 min to complete. Next, a narrow BL-RHI scan composed of 11 RHIs within 10° of the wind direction (2° increment) and from 0 to 80° elevation is proposed (5 min) followed by ~ 20 min crosswind range-height indicator (CW-RHI) from horizon to horizon, i.e., across the helical roll circulations. The aforementioned sequence should take no more than 30 minutes. In the next 30 min, the Ka/WSACR will repeat the HS-RHI+PPI scan and then perform a vertically pointing type (VPT) sequence to enable profiling dual-frequency analyses (KAZR and WSACR). The VPT scan will last for ~25 min. The proposed scan sequence (HS-RHI+PPI, BL-RHI, CW-RHI, HS-RHI+PPI+VPT) will be repeated every hour.

Radiosondes. Twice-daily radiosondes are released from the ENAN site (WMO identifier 01010) located next to the Andenes high school (Figure 3). We would like to supplement this with ARM-provided radiosondes released every three hours during PI-defined intensive operational periods (IOPs) (cold-air outbreaks or polar lows). The climatology suggest that CAO conditions apply up to ~20% of the time in JFMAM, i.e. that IOPs will occur on ~30 days of the 5-month deployment, mostly in the first three months. Assuming that ARM personnel can launch eight additional soundings per day, we are requesting 240 sondes. If the ARM crew duty limitations limit the soundings to say 5 per day (3 hourly, over a 15- hour period), then we request 5*30=150 sondes, plus the necessary helium and balloons.

Aerosol observing system: The AOS is a mostly self-contained lab. Because the AOS is essentially a stand-alone container that cannot be easily modified to replace any aerosol instrument deemed non-essential (i.e., those that are not category 1) with other instruments and because a majority of the aerosol probes are ranked category 1, we are requesting the complete suite of aerosol probes to be installed with the AOS to sample the boundary-layer characteristics. Nevertheless, a complete priority listing of the probes is given in Table 5 to facilitate ARM probe deployment planning. Because many of our goals involve understanding the sources and sinks of aerosols, CCN and INPs, or their correlation with cloud parameters, most of the instruments are category #1.

Table 5. AOS priority listing.

AOS probe	Measured variables	Priority	Why important?
ACSM	Mass concentrations of organics, sulfate, nitrate, ammonium, and chloride	2	For aerosol composition
CCN-200	Concentration of cloud condensation nuclei at various supersaturations	1	To understand cloud/aerosol relationships
$CO/N_2O/H_2O$ and O_3	Gas mixing ration sensors	1	Important tracer of pollutants and origin of aerosols
CPC-3772 (fine)	Concentration of sub-micron aerosol particles	1	Small aerosols give information about formation
UHSAS	Concentration and size distribution of sub-micron aerosol particles	1	provides aerosol information at much better time resolution than HTDMA
HTDMA	The rate at which aerosol particles deliquesce at increasing RH	2	Size-resolved aerosol hygroscopic properties for cloud-aerosol questions
Nephelemeter	Total scattering and hemispheric backscattering of aerosol, both at ambient RH and at variable controlled RH (like the HTDMA)	1	Aerosol hygroscopic scattering properties
PSAP	Change in light transmission on a filter exposed to ambient aerosol, relative to a reference filter	1	For understanding black carbon

7.2 User-Supplied Instruments

Ice-Nucleating Particles

The AOS measures aerosol size distribution and aerosol condensation characteristics, but it does not measure the temperature-dependent concentration of ice-nucleating particles (INP). *The COMBLE award includes support for INP to be measured at Andenes during the duration of COMBLE*. Such measurements will complement the upstream INP measurements at Ny-Ålesund (Section 6.3), and are needed to address science theme #4 and associated hypothesis. Specifically, Paul DeMott's team at Colorado State University (CSU) will be supported to coordinate filter-based collections and post- processed immersion freezing measurements of INP.

The samples will be collected for 48-hour periods, except around outbreak events when the sampling interval will be ~24 hours or whatever is needed to capture air mass change. The longer sampling intervals should allow immersion freezing spectra of high detail to temperatures as warm as -5°C. First samples will be sent back to CSU after one month of operation to check these assumptions, and then again at the end of the study period, using the specific frozen shipping protocol that their team has identified as necessary to maintain sample integrity.

7.3 Site Considerations

The town of Andenes (Figure 3) is on the north side of the island of Andöja, which is connected by road to the mainland, and close to the regional hub of Tromsö. Andenes has a commercial airport and some 2500 permanent inhabitants. The closest operational C-band radar (Trolltinde) is nearby, with good views of Andenes and the offshore area (Figure 3). There also is a 140-m-high weather tower, which is not equipped at this time, but may be equipped in 2020 through a grant from the Norwegian Research Council to the Andoya Space Center (PI: Thomas Spengler).

The best location for AMF1 is Nordmela Harbor, as it comes closest to capturing the offshore cloud and precipitation structure without local aerosol contamination. The precise choice of location for AMF1 must depend on a number of factors, including access to power and communication cables, the presence of obstacles for scanning radar, especially to the northern sector, and, for the AOS, the presence of local aerosol and trace-gas sources. Broadband communication and accommodations are excellent in Andenes. The town hosts the Andoya Space Center, which includes the Alomar Observatory (http://andoyaspace.no/?page_id=19), located on a hill just south of town (Figure 3). The observatory includes active and passive remote-sensing instruments that cover the atmosphere from the ground to the upper atmosphere.

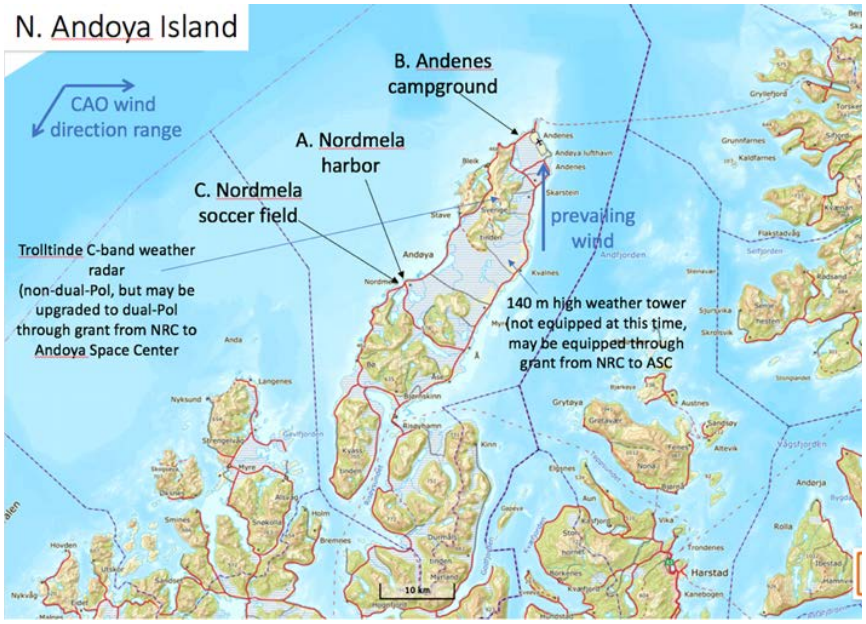

Figure 3. Terrain map of northern Andoya Island, showing three possible AMF1 locations, in order of preference (first choice is Nordmela Harbor).

8.0 Instruments on Bear Island (Bjørnøya)

8.1 AMF Instruments

We request a subset of AMF probes to operate on Bear Island (Figure 2) during the duration of COMBLE (1 January31–May, 2020).

The instrument list is shown in Table 6.

Table 6. Priority table for the AMF satellite on Bear Island.

Instrument	Measurement	Priority
MWRP	Temperature and humidity profiles	1
MPL (profiling) + CEIL	Backscatter power, aerosol layers, cloud base	1
TSI	Cloud fraction	1
LDIS	Precipitation size distribution, fallspeed	1
MET	Surface meteorology, precipitation	2
RWP (1290 MHz)	Wind profiles (probably not available)	1
ECOR	Eddy correlation surface fluxes	1
CEIL	ceilometer	1
MFRSR	Multi-filter rotating shadowband radiometer	2
Sun photometer	Narrow FOV radiances	2
VIS and IR broadband radiometer	SW and LW surface radiation budget	2
Radiosondes (150 total)	T, q, wind profiles	1

The ARM Mobile Facilities instrument manager (Kim Nitschke) told us that this list should be feasible, with the possible exception of the TSI. The ECOR needs to be located along the upwind shore.

Radiosondes: Meteo Norway will launch four sondes per day from Bear Island during COMBLE. We are requesting four additional soundings on CAO days only (120 ARM radiosondes in total), to be launched by Meteo Norway staff, using their own balloons and gas (hydrogen). This enables three-hourly interval sondes during COMBLE IOPs, at the same time as the ENAN and ARM radiosondes from Andenes. Meteo Norway has agreed to have its personnel releasing these ARM-provided radiosondes, subject to crew duty limitations.

8.2 User-Supplied Instruments

At this time two user-provided probes are considered, both Ka-band profiling radars:

- A micro-snow radar (MSR), i.e., a Metek Micro-Rain Radar Pro (MRR-Pro) modified for snow observations, to be provided by Max Maahn, subject to success in a pending proposal
- A standard micro-rain radar (MRR), provided by S. Crewell at the University of Cologne. The MRR will be deployed only if the MSR proposal is not funded.

No ARM support will be requested for the installation and operation of the MRR or MSR. An ARM Instrument Support Request (ISR) is on file for both instruments.

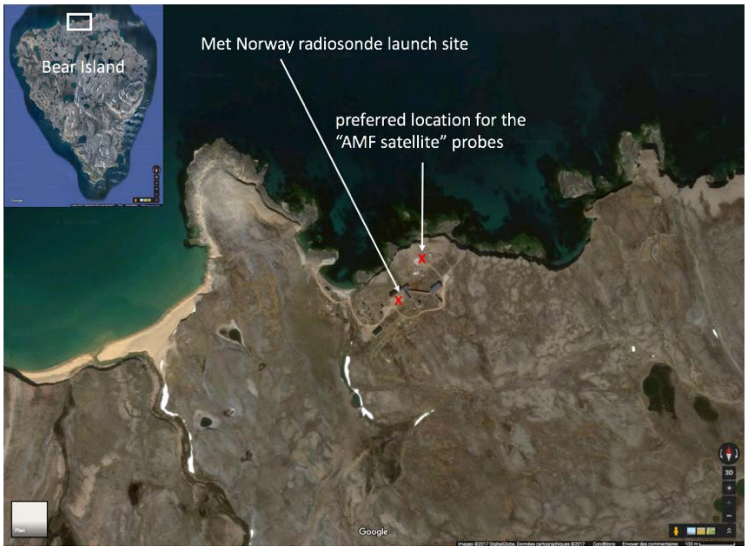

Figure 4. Google Earth map of the Meteo Norway weather station on the north side of Bear Island (74°31′N, 19°01′E).

8.3 Site Considerations

Bear Island is about 12 km wide (east-west distance). Its highest elevation is 536 m. Thus the (northerly) flow is expected to be deflected, impacting clouds and precipitation, but not blocked as the convective boundary layer should be considerably deeper.

Bear Island is a nature reserve and is uninhabited. Meteo Norway maintains a year-round-manned weather and communications station near the north shore of the island (Figure 4), with a normal crew of six. Sea containers cannot be unloaded onto the island as there is no dock. Lighter instruments (i.e., those not requiring sea containers) and other supplies can be loaded/unloaded using a small vessel moving between an anchored cargo ship and the beach just west of the weather station. The waters around Bear Island do not freeze in winter.

Regarding data transfer, Meteo Norway plans to make available at least one fixed internet protocol (IP) address via broadband satellite for use by ARM on Bear Island. The data rate in 2020 remains to be determined. As of spring 2017, four fixed IPs share a stable line with a capacity of 20 Megabits per second (Mbps) download and 6 Mbps upload. Meteo Norway is planning to deliver up to four fixed IP addresses via broadband satellite to the external partners on Bear Island during COMBLE. The shared download (upload) capability should be 20 (6) Mbps.

Meteo Norway can accommodate ARM personnel for short periods for instrument installation and tear- down. It will also provide technical staff throughout the COMBLE field phase, for instrument troubleshooting and maintenance. See Appendix 1 for details.

9.0 Relevance to the Mission of DOE/BER

Because general circulation models (GCMs) are the primary tool policymakers use to determine acceptable levels of greenhouse gases in the atmosphere, their improvement and evaluation is needed to accomplish Biological and Environmental Research (BER)’s long-term measure of scientific advancement: to understand the role of Earth’s biogeochemical systems (atmosphere, land, oceans, sea ice, subsurface) in determining climate in order to predict climate decades or centuries into the future, information needed to plan for future energy and resource needs. 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 GCMs, especially related to the radiative forcing of the climate system. One particular region where models need improvement is in high- latitude regions. The Arctic in particular is currently warming faster than the rest of the Earth (Arctic Climate Impact Assessment [ACIA] 2005) and at a rate faster than predicted by models (Solomon et al. 2007). Previous 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 there are large uncertainties in climate projections due to the inadequate treatment of aerosol-cloud effects, calling for better process models at multiple scales for aerosol, clouds, radiation, and precipitation. More broadly, COMBLE falls in the BER priority area of high-latitude atmosphere-ocean-ice-ecosystem interactions and processes.

The COMBLE campaign seeks to acquire a data set suitable to study interactions between microphysics, dynamics, and radiative transfer in arctic clouds associated with cold-air outbreaks, and to provide a data set suitable for the development and evaluation of parameterizations for models with a variety of spatial and temporal scales, as well as for ground- and space-based remote-sensing retrievals. Hence, COMBLE is very appropriate for deployment of the AMF since the ARM Decadal Mission statement (2014) calls for the deployment of AMF in regions where measurements are most needed for climate research.

The COMBLE data will lead to an improvement in the representation of shallow, precipitating convection in regional and global climate models, through the evaluation and improvement of shallow convection and boundary-layer parameterizations and thus is highly appropriate for the deployment of the AMF. The COMBLE deployment also contributes to the mission of BER within DOE by collecting data with a scientific user facility that will be used to support fundamental research and “advance understanding of the roles of Earth’s biogeochemical systems (the atmosphere, land, oceans, sea ice, and subsurface) in determining climate so we can predict climate decades or centuries into the future.” Further, it will contribute to the performance goal of BER which to “develop capabilities to improve understanding of critical sub-decadal processes and incorporate the results into Earth system models.”

COMBLE also contributes to the mission of the Climate and Environmental Sciences Division (CESD) of BER by using “the unique capabilities and impacts of the ARM and the EMSL (Environmental Molecular Sciences Laboratory) scientific user facilities and other BER community resources to advance the frontier of climate and environmental science” by “advancing studies to enhance the understanding of atmospheric and terrestrial system processes.” The COMBLE data, to be obtained in a region where few observations exist, also will contribute to the primary objective of the ARM user facility of CESD by “providing a detailed and accurate description of the Earth’s atmosphere in [a] diverse climate regime to resolve the uncertainties in climate and Earth system models,” thereby furnishing “the climate research community with strategically located in situ and remote-sensing observatories designed to improve the understanding and representation in climate and Earth system models, of clouds and aerosols as well as their interactions and coupling with the Earth’s surface.”

10.0 Data Management Plan

The installation of the ARM facilities and communication links, the troubleshooting, maintenance and performance assessment of probes, and the collection, storage, and transfer of data in COMBLE will require a rather high level of collaboration between Meteo Norway and ARM, especially at Bear Island.

Fortunately, Meteo Norway is keen to contribute to COMBLE not just as a service to the international climate science community but also as a way to evaluate and improve its own modeling capabilities, mainly in the context of improved forecasting of adverse weather conditions. A Letter of Intent from Dr. Cecilie Stenersen, Director Observations and Climate, Meteo Norway, is included as Appendix 1.

This letter addresses current networking and communications capabilities on Bear Island, and plans to ensure a reliable network connection to the AMF “satellite” probes and associated components. It also mentions the availability of a technician to assist with the troubleshooting and maintenance of instruments and communications equipment, as well as access to Meteo Norway’s operational C-band radar data and numerical model output. Not mentioned in the letter is Meteo Norway’s support for radiosonde balloons. In principle Meteo Norway is willing to provide personnel on Bear Island to release sondes and collect the data, as long as the work falls within crew duty limitations. If COMBLE receives a green light, then further discussions with Meteo Norway will be needed.

We trust that ARM personnel will assume responsibility for:

1. the overall configuration and operation for the data systems of AMF1 (at Andenes) and of the AMF satellite (on Bear Island), including the system startup sequence, operational monitoring, and shutdown sequence;

2. the data processing, quality control (QC), and transfer of AMF data to the ARM Data Center;
3. the assessment of the quality of the AMF data, including quality assurance limits and ranges.

The COMBLE scientists will work with ARM personnel to ensure the delivery, evaluation, and archiving of certain "value-added" or "derived" products, that build on a combination of data from different instruments, including possible radiosonde or model output data. Examples include an estimate of the hydrometeor fallspeed and air vertical motion from the Doppler spectrum of KAZR data.

Users providing their own instrument to Bear Island or Andenes may be able to take advantage of the networking and communications capabilities installed for the AMF probes, but otherwise are fully responsible for the data processing, QC, and archiving of their data. They are bound by the data policy of their own funding agency, but are encouraged to join ARM in a fully open data policy without embargo period. An arrangement may be made for these user-provided data sets to be archived at the ARM Data Center as well.

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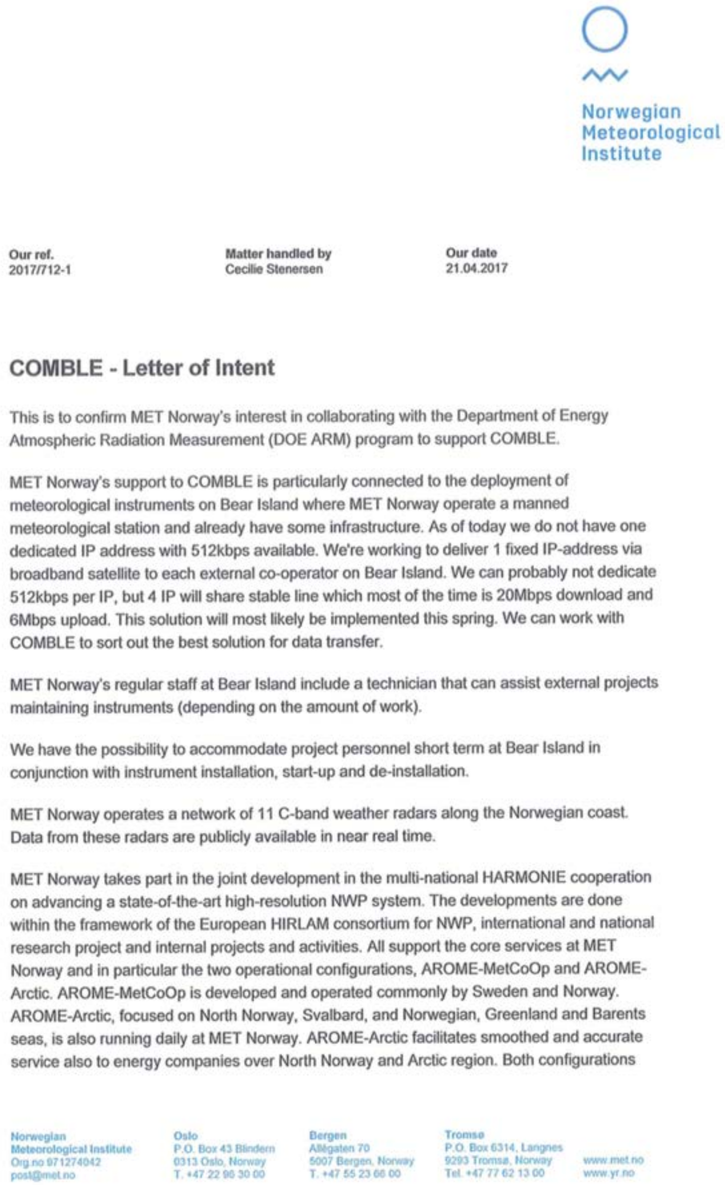
Appendix A

Letter of Intent from Meteo Norway



Norwegian
Meteorological
Institute

Our ref.	Matter handled by	Our date
2017/712-1	Cecilie Stenersen	21.04.2017

COMBLE - Letter of Intent

This is to confirm MET Norway's interest in collaborating with the Department of Energy Atmospheric Radiation Measurement (DOE ARM) program to support COMBLE.

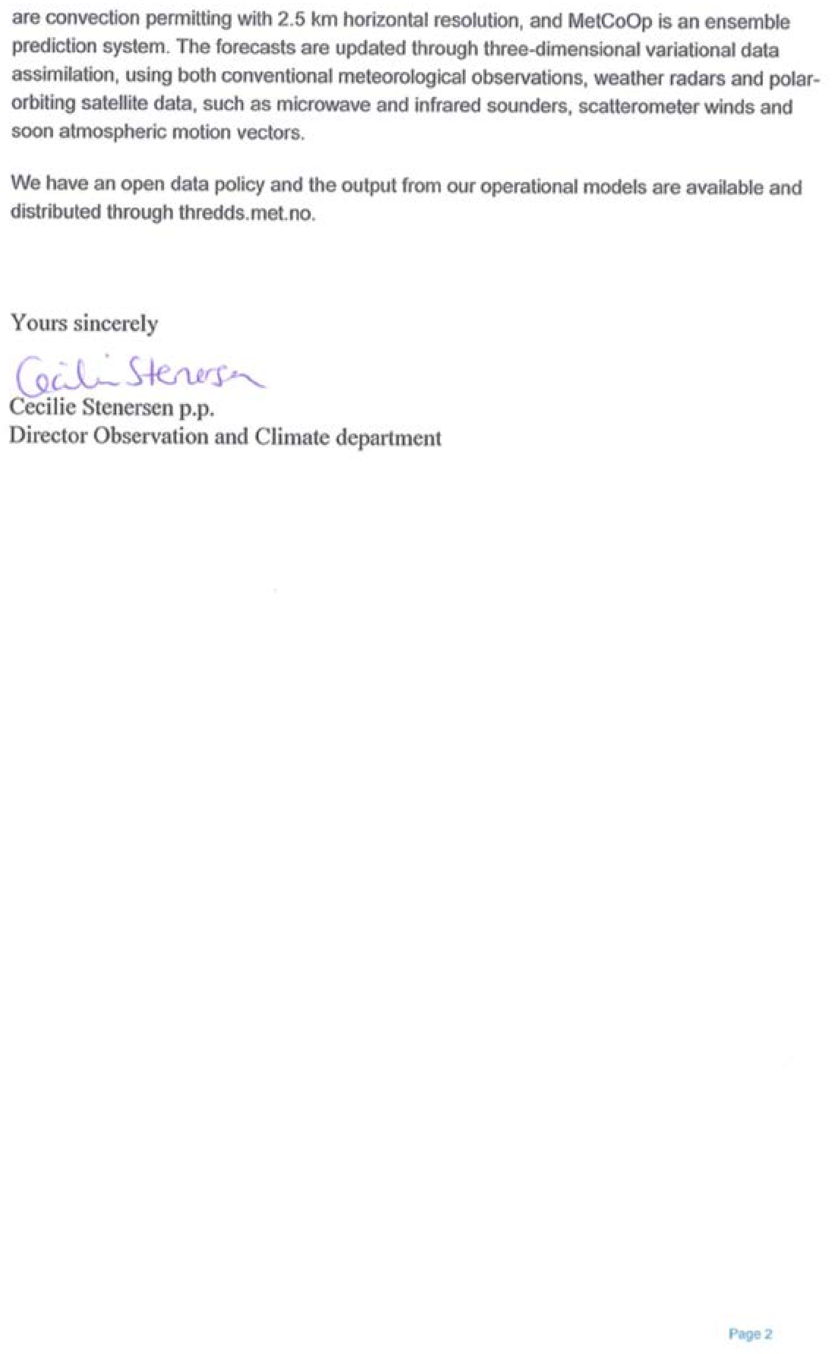
MET Norway's support to COMBLE is particularly connected to the deployment of meteorological instruments on Bear Island where MET Norway operate a manned meteorological station and already have some infrastructure. As of today we do not have one dedicated IP address with 512kbps available. We're working to deliver 1 fixed IP-address via broadband satellite to each external co-operator on Bear Island. We can probably not dedicate 512kbps per IP, but 4 IP will share stable line which most of the time is 20Mbps download and 6Mbps upload. This solution will most likely be implemented this spring. We can work with COMBLE to sort out the best solution for data transfer.

MET Norway's regular staff at Bear Island include a technician that can assist external projects maintaining instruments (depending on the amount of work).

We have the possibility to accommodate project personnel short term at Bear Island in conjunction with instrument installation, start-up and de-installation.

MET Norway operates a network of 11 C-band weather radars along the Norwegian coast. Data from these radars are publicly available in near real time.

MET Norway takes part in the joint development in the multi-national HARMONIE cooperation on advancing a state-of-the-art high-resolution NWP system. The developments are done within the framework of the European HIRLAM consortium for NWP, international and national research project and internal projects and activities. All support the core services at MET Norway and in particular the two operational configurations, AROME-MetCoOp and AROME-Arctic. AROME-MetCoOp is developed and operated commonly by Sweden and Norway. AROME-Arctic, focused on North Norway, Svalbard, and Norwegian, Greenland and Barents seas, is also running daily at MET Norway. AROME-Arctic facilitates smoothed and accurate service also to energy companies over North Norway and Arctic region. Both configurations



are convection permitting with 2.5 km horizontal resolution, and MetCoOp is an ensemble prediction system. The forecasts are updated through three-dimensional variational data assimilation, using both conventional meteorological observations, weather radars and polar-orbiting satellite data, such as microwave and infrared sounders, scatterometer winds and soon atmospheric motion vectors.

We have an open data policy and the output from our operational models are available and distributed through thredds.met.no.

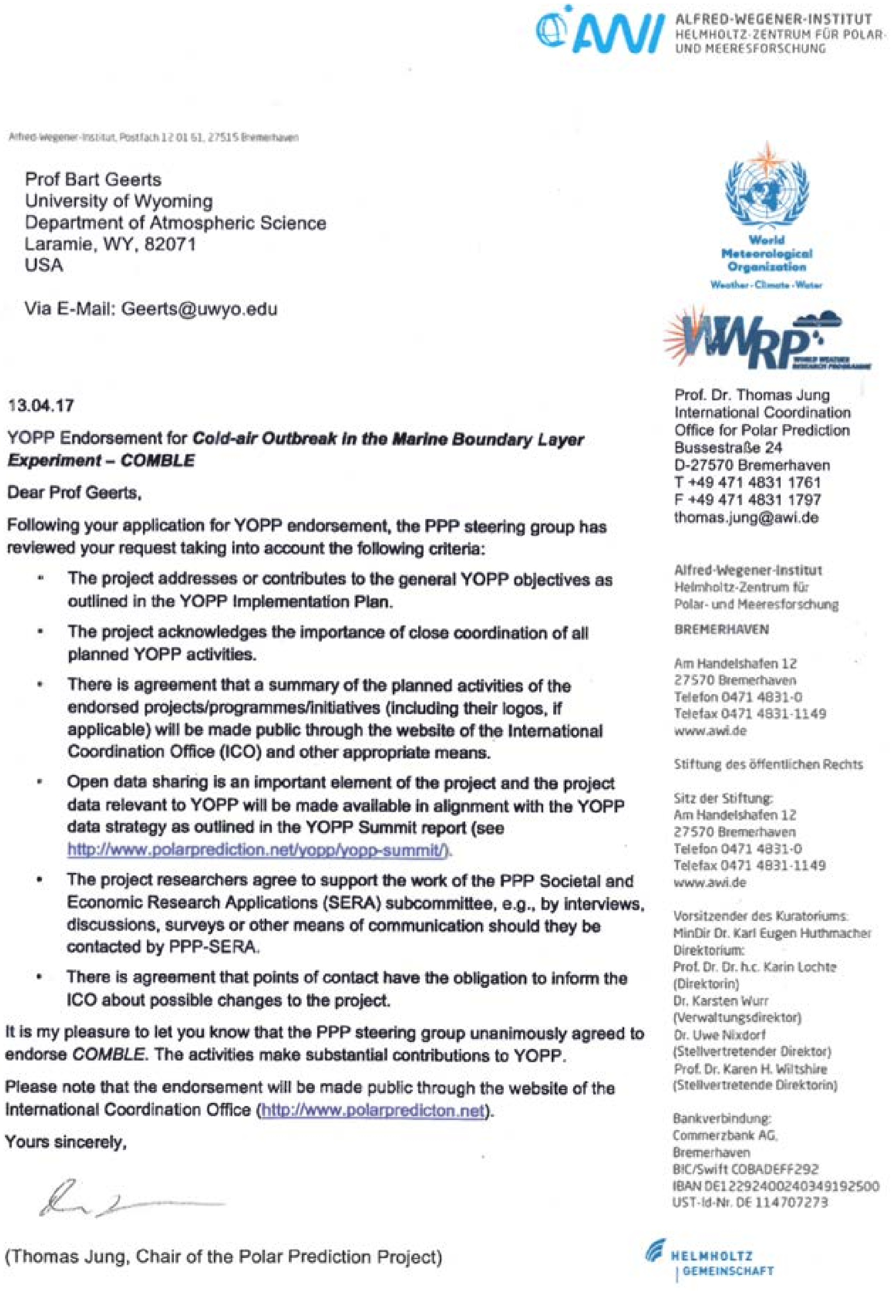
Yours sincerely

Cecilie Stenersen

Cecilie Stenersen p.p.
Director Observation and Climate department

Appendix B

Endorsement from the YOPP Committee



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UND MEERESFORSCHUNG

Alfred-Wegener-Institut, Postfach 12 01 61, 27515 Bremerhaven

Prof Bart Geerts
University of Wyoming
Department of Atmospheric Science
Laramie, WY, 82071
USA

Via E-Mail: Geerts@uwyo.edu

13.04.17

YOPP Endorsement for ***Cold-air Outbreak in the Marine Boundary Layer Experiment – COMBLE***

Dear Prof Geerts,

Following your application for YOPP endorsement, the PPP steering group has reviewed your request taking into account the following criteria:

- **The project addresses or contributes to the general YOPP objectives as outlined in the YOPP Implementation Plan.**
- **The project acknowledges the importance of close coordination of all planned YOPP activities.**
- **There is agreement that a summary of the planned activities of the endorsed projects/programmes/initiatives (including their logos, if applicable) will be made public through the website of the International Coordination Office (ICO) and other appropriate means.**
- **Open data sharing is an important element of the project and the project data relevant to YOPP will be made available in alignment with the YOPP data strategy as outlined in the YOPP Summit report (see http://www.polarprediction.net/yopp/yopp-summit/).**
- **The project researchers agree to support the work of the PPP Societal and Economic Research Applications (SERA) subcommittee, e.g., by interviews, discussions, surveys or other means of communication should they be contacted by PPP-SERA.**
- **There is agreement that points of contact have the obligation to inform the ICO about possible changes to the project.**

It is my pleasure to let you know that the PPP steering group unanimously agreed to endorse *COMBLE*. The activities make substantial contributions to YOPP.

Please note that the endorsement will be made public through the website of the International Coordination Office (http://www.polarpredicton.net).

Yours sincerely,

(Thomas Jung, Chair of the Polar Prediction Project)

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Organization
Weather · Climate · Water

WWRP

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Dr. Karsten Wurr
(Verwaltungsdirektor)
Dr. Uwe Nixdorf
(Stellvertretender Direktor)
Prof. Dr. Karen H. Wiltshire
(Stellvertretende Direktorin)

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Appendix C

ARM Resources

ARM resources: AMF1, AOS, plus a select array of instruments (AMF-lite)

Location: AMF1 and AOS: Andenes, Norway; AMF-lite: Bear Island, Norway

Duration: 1 January–31 May, 2020

Investigators:

Name	**Affiliation**	**Email**	**Interests***
Bart Geerts, PI	University of Wyoming	geerts@uwyo.edu	cloud radar, lidar, and in situ cloud measurements, mesoscale structure
Greg McFarquhar	University of Illinois	mcfarq@illinois.edu	cloud particle measurements
Lulin Xue	National Center for Atmospheric Research	xuel@ucar.edu	modeling aerosol-cloud-precipitation; LES, and mesoscale
Michael Tjernström	Stockholm University	michaelt@misu.su.se	Arctic boundary-layer structure and clouds, and BL transformation
Pavlos Kollias	Stony Brook University and Brookhaven National Laboratory	pkollias@bnl.gov	radar, clouds, and precipitation
Michael Jensen	Brookhaven National Laboratory	mjensen@bnl.gov	BL cloud properties and processes, BL thermodynamics
Mikhail Ovchinnikov	Pacific Northwest National Laboratory	Mikhail.Ovchinnikov@pnnl.gov	cloud process modeling and parameterizations
Thomas Spengler	University of Bergen	Thomas.Spengler@uib.no	dynamics of polar lows and CAOs
Matthew Shupe	University of	matthew.shupe@noaa.gov	clouds, radiation, and

Name	Affiliation	Email	Interests*
	Colorado and NOAA-ESRL		surface-coupled processes, MOSAIC liaison
Paul DeMott	Colorado State University	Paul.Demott@colostate.edu	INP measurements, aerosol size distribution
Susanne Crewell	University of Cologne	crewell@meteo.uni-koeln.de	integration of ground-based and satellite remote sensing
Roel Neggers	University of Cologne	rneggers@uni-koeln.de	CAO modeling, LES
Manfred Wendisch	University of Leipzig	m.wendisch@uni-leipzig.de	radiative impact of mixed-phase clouds
Christof Lüpkes	Alfred Wegner Institute (AWI) Bremerhaven	christof.luepkes@awi.de	surface energy fluxes
Steven Abel	UK Met Office	steven.abel@metoffice.gov.uk	In situ measurements and modeling of clouds and precip in CAOs
Paul Field	UK Met Office	paul.field@metoffice.gov.uk	In situ measurements and modeling of clouds and precip in CAOs
Yonggang Wang	Texas Tech Univ.	yonggang.wang@ttu.edu	validation of model cloud and precipitation

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