Atmospheric processes in the marine CAO regime, based on COMBLE observations and modelling

Cold-Air Outbreaks in the Marine Boundary Layer Experiment

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ARM CLIMATE RESEARCH FACILITY

ASR Atmospheric System Research

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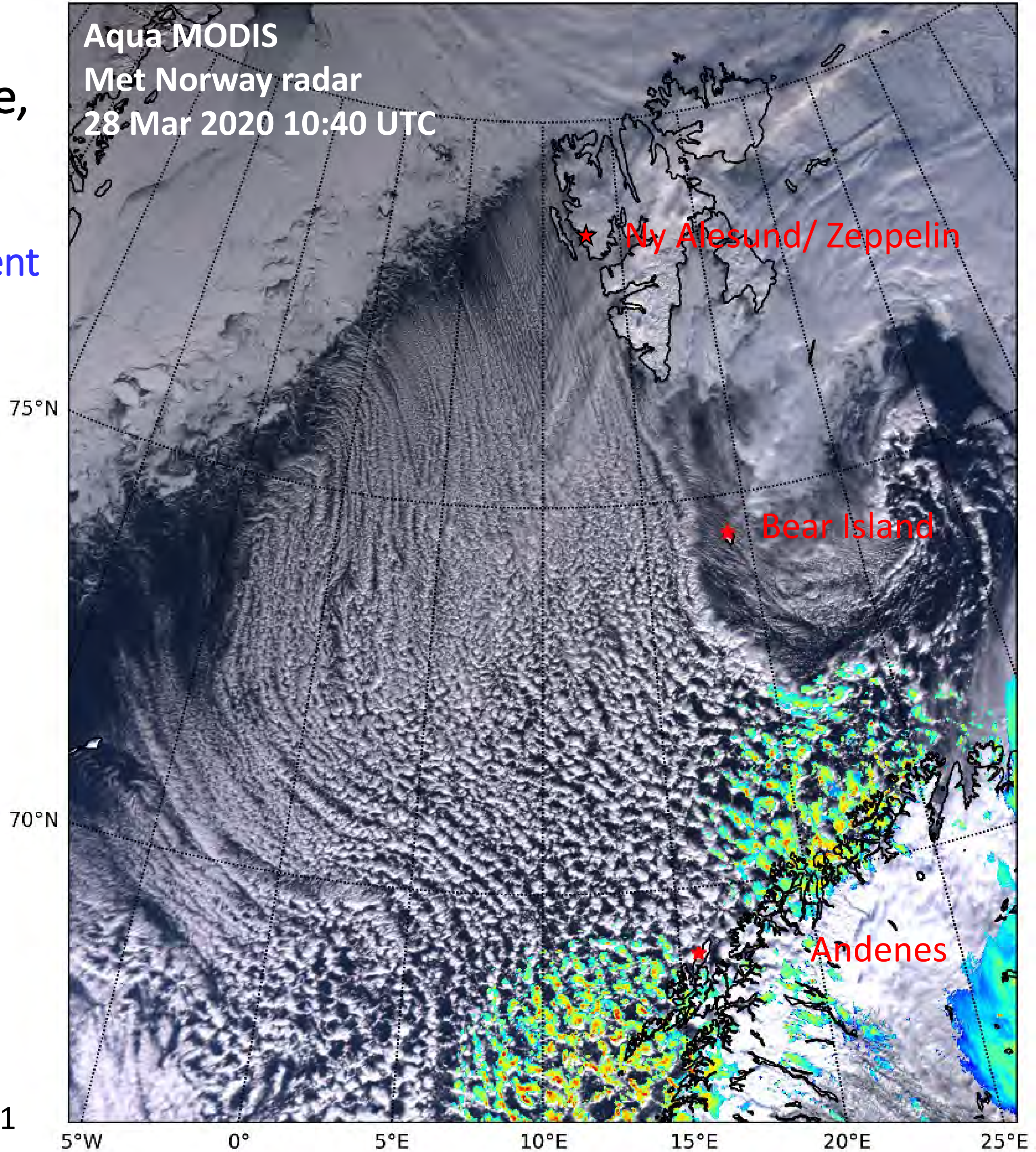
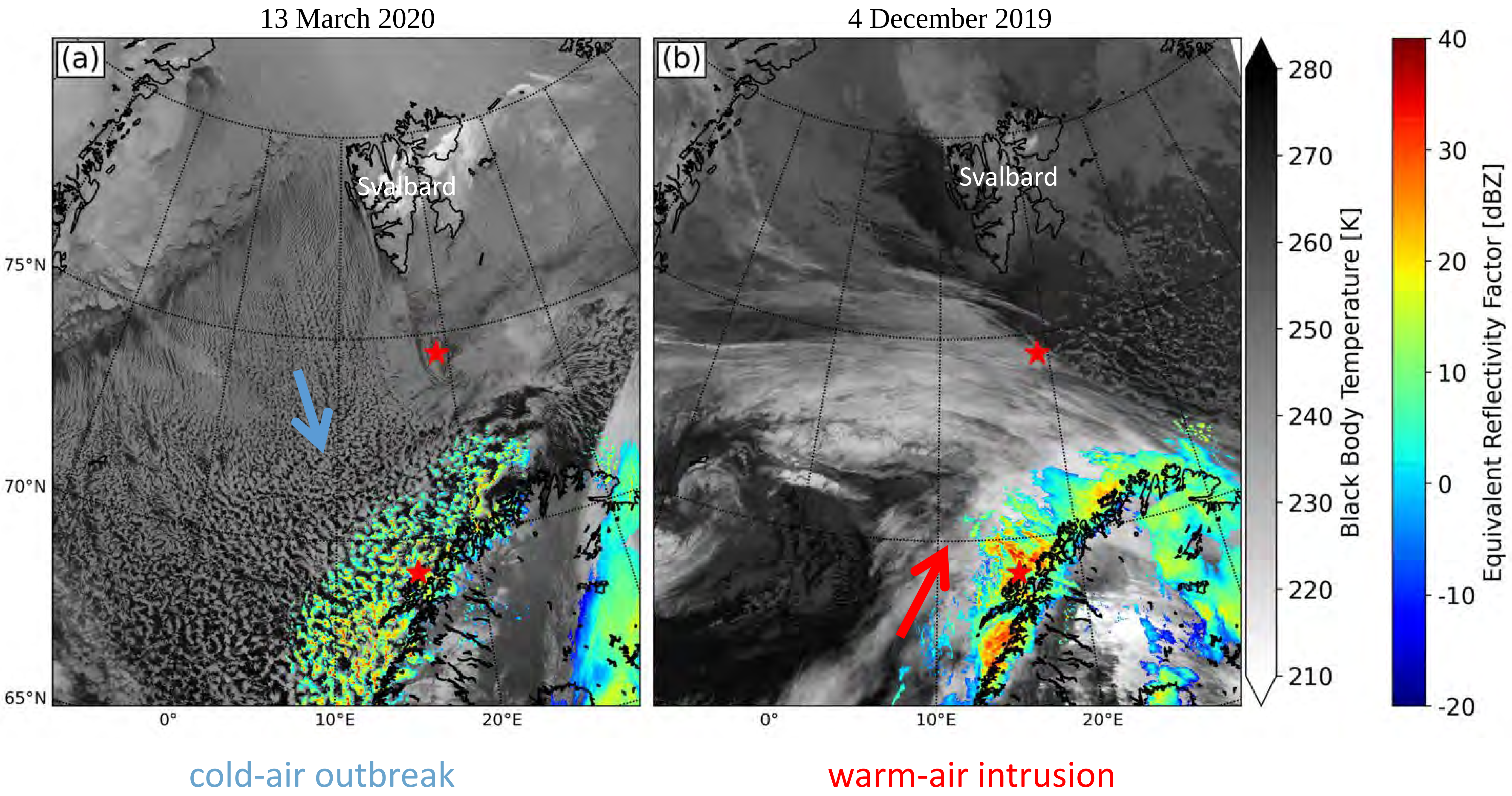
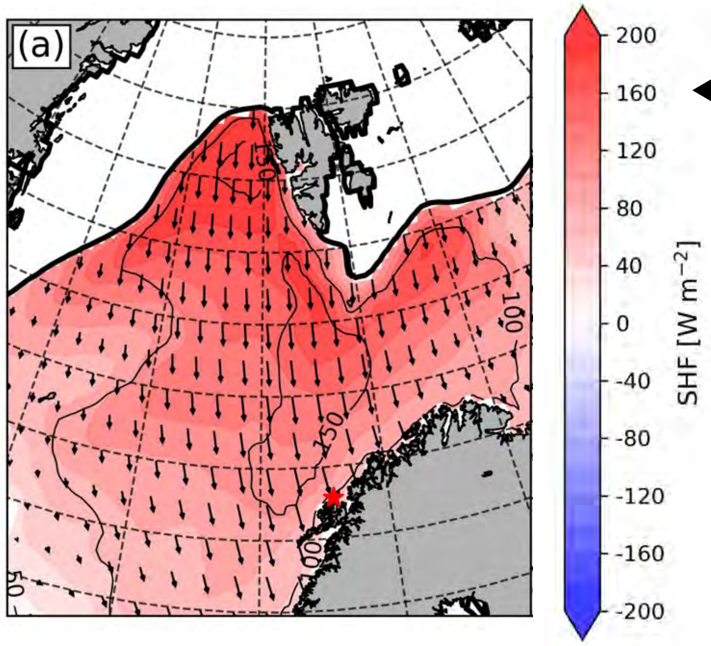




13 March 2020
4 December 2019
(a)
(b)
Svalbard
Svalbard
75°N
70°N
65°N
0°
10°E
20°E
0°
10°E
20°E
280
270
260
250
240
230
220
210
Black Body Temperature [K]
40
30
20
10
0
-10
-20
Equivalent Reflectivity Factor [dBZ]
cold-air outbreak
warm-air intrusion

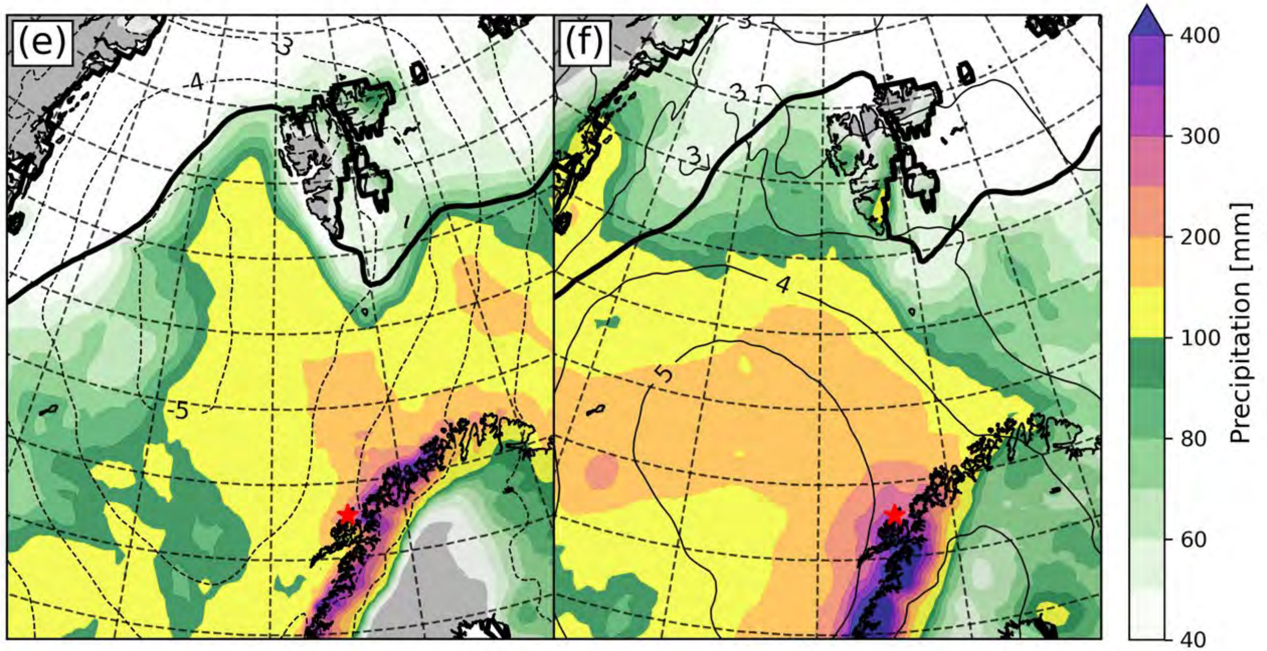
Surface sensible heat flux (color fill)
latent heat flux (contours, W m^{-2})
10 m winds (vectors)



cold-air outbreaks

COMBLE composites (6 months, ERA5 data)

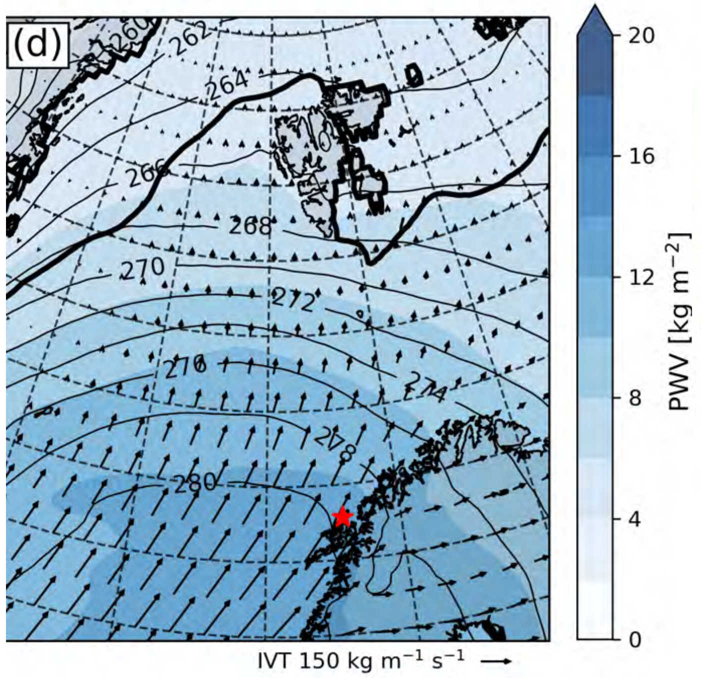
Total precipitation, 850 hPa temperature anomaly (K)



cold-air outbreaks

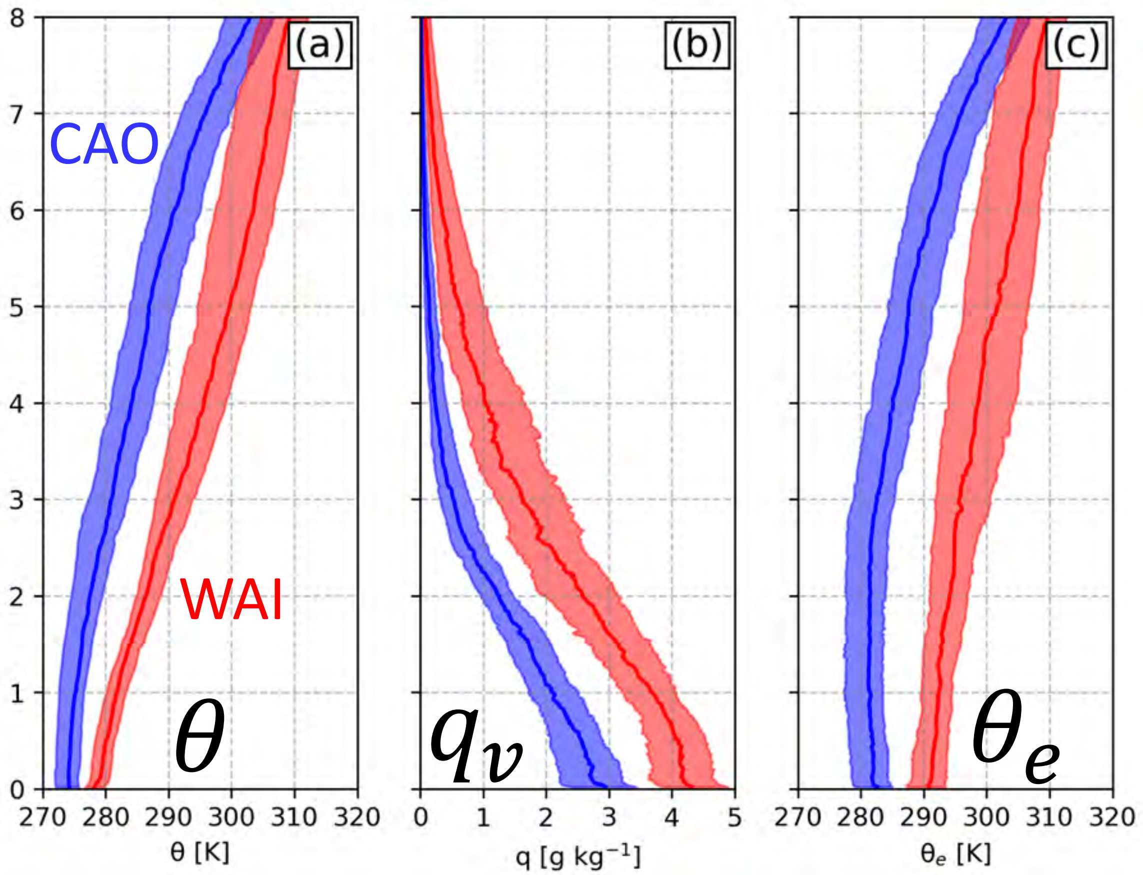
warm-air intrusions

warm-air intrusions

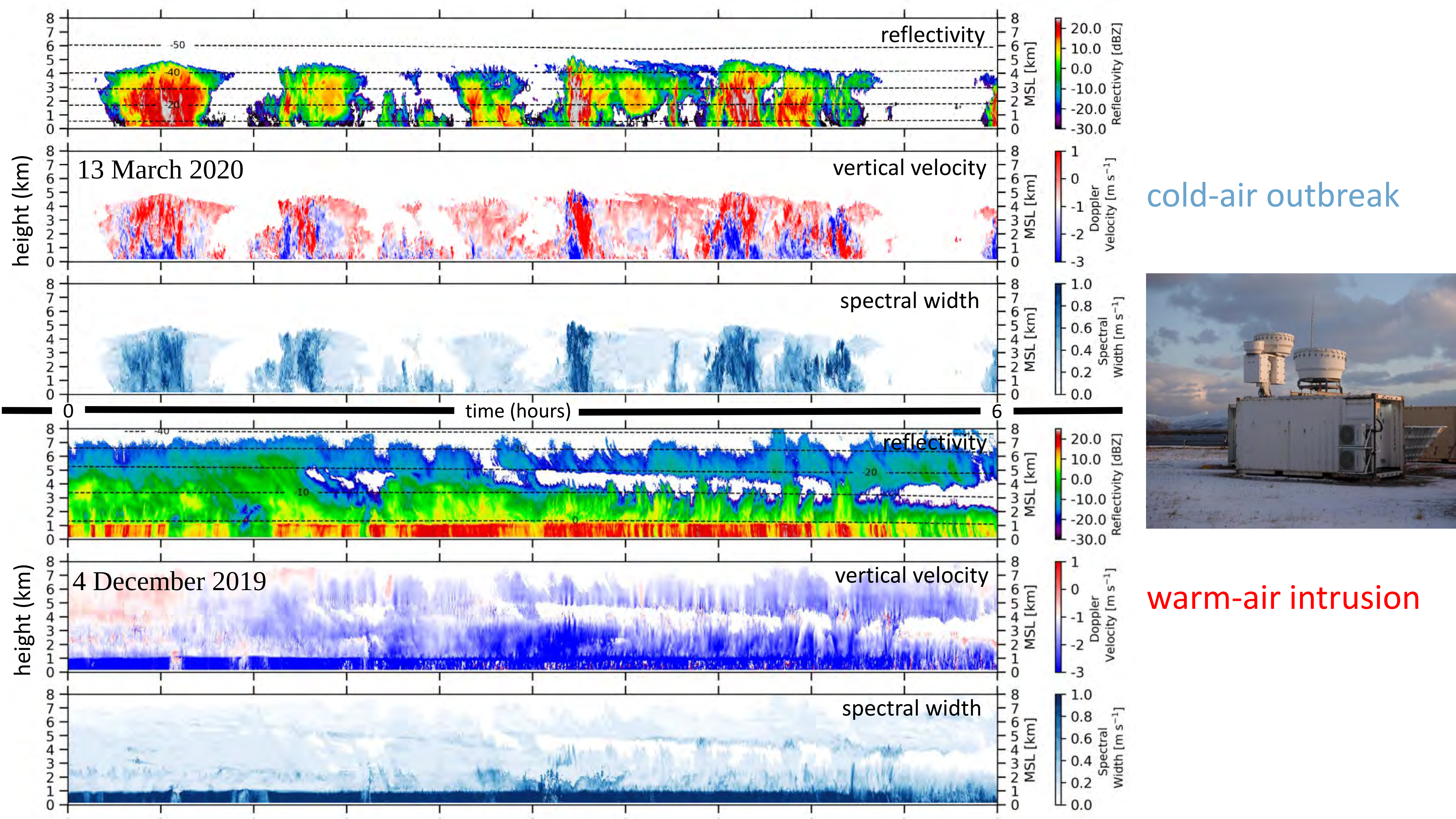


Precipitable water vapor (color)
850 hPa θ_e (contours, K)
IVT (vectors)

COMBLE composites (ERA5 data)



cold-air outbreaks warm-air intrusions

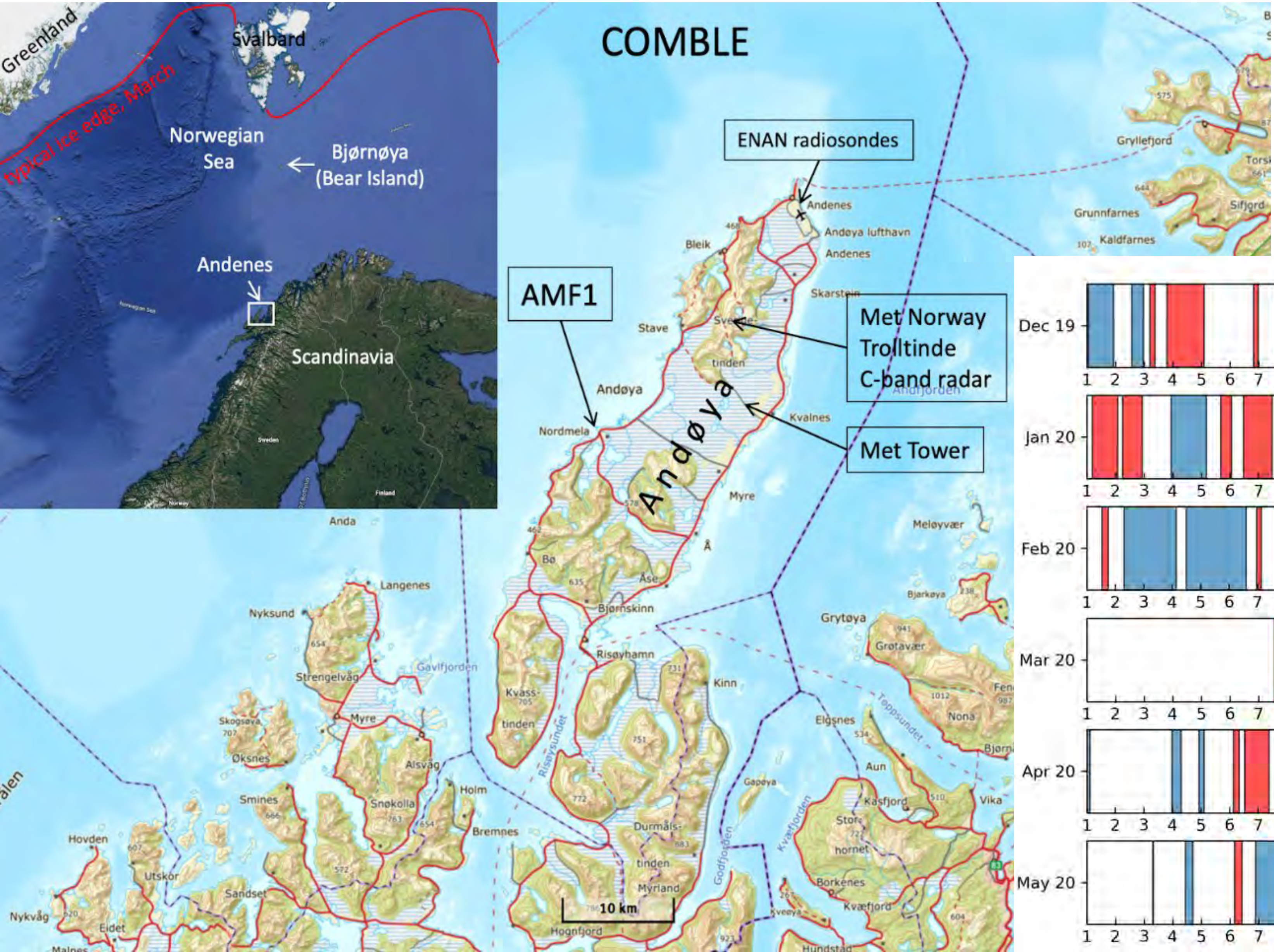


reflectivity
13 March 2020
vertical velocity
spectral width
height (km)
MSL [km]
Reflectivity [dBZ]
Doppler Velocity [m s⁻¹]
Spectral Width [m s⁻¹]
cold-air outbreak
time (hours)
0
6
4 December 2019
warm-air intrusion

Representing marine CAOs in weather and climate models is difficult

- Key processes driving the CAO cloud regime are in a ***grey zone***
  - Surface fluxes strongly affected by unresolved circulations
  - Clouds and precip processes driven by unresolved coherent BL circulations
  - Radiative and precipitation properties sensitive to aerosol
- Resolved **mesoscale cloud organization is very sensitive** to model resolution and domain size
- The CAO cloud regime serves as **an excellent natural testbed** to examine the representation of aerosol and mixed-phase cloud processes in models

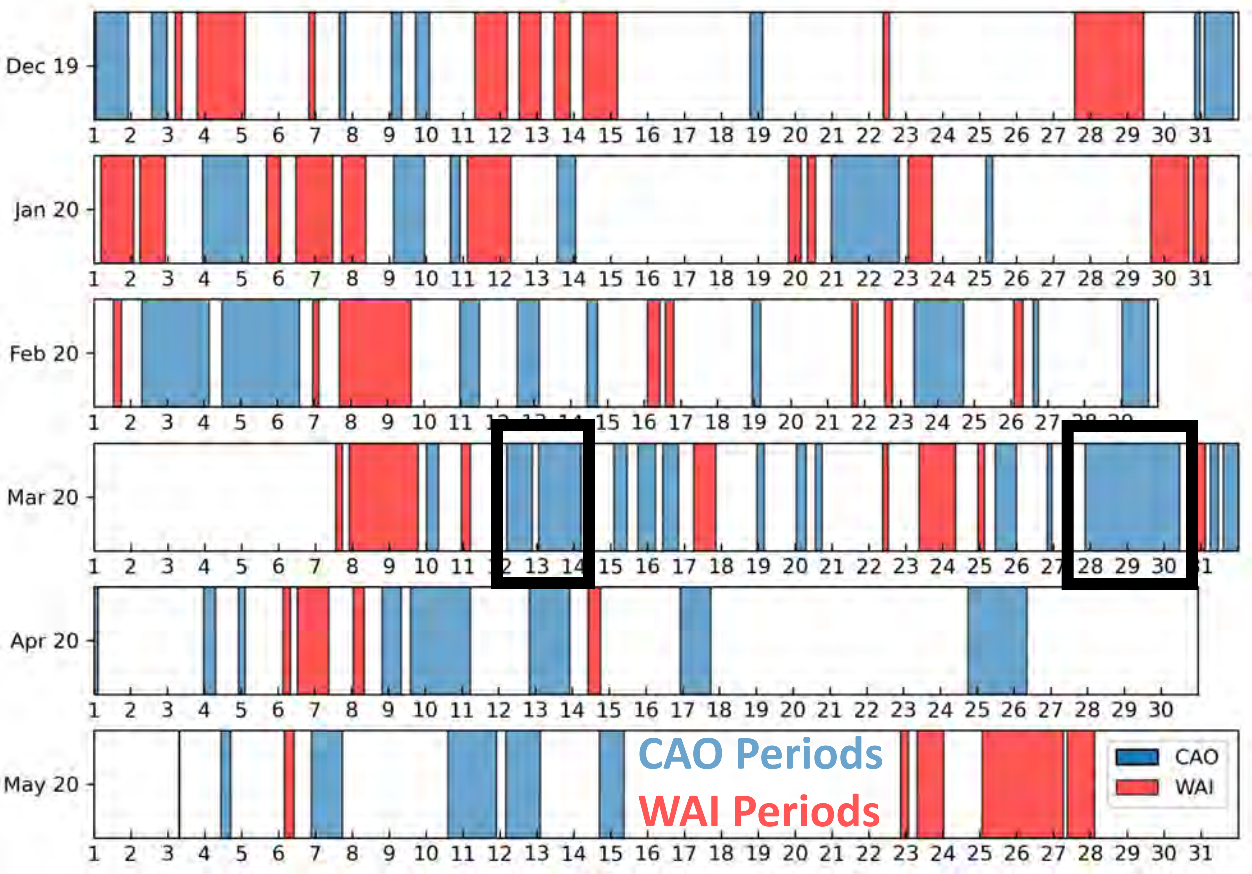
COMBLE: Cold-Air Outbreaks in the Marine Boundary Layer Experiment



1 Dec '19 – 31 May '20

CAO: $M \equiv \theta_{SST} - \theta_{850\,hPa} > 0$

WAI: $S \equiv \theta_{e,850mb} - \theta_{e,surface} > 0$



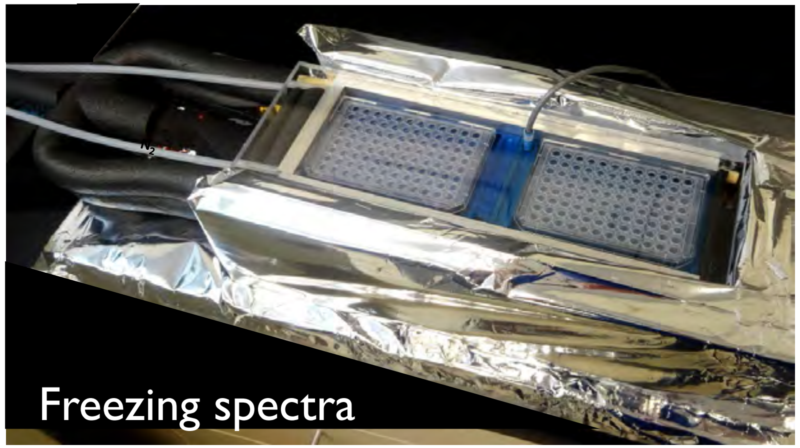
COMBLE instruments: Andøya

Instrument	Measurement
Ka-SACR and W-SACR (scanning)	35 and 95 GHz reflectivity, Doppler velocity, Doppler spectrum
KAZR (profiling)	35 GHz reflectivity, Doppler velocity
AERI (Atm. Emitted Radiance Interferom.) & MWRP (microwave radiometer)	temperature and humidity profiles
~~MPL (profiling micro pulse lidar)~~ part-time	backscatter power
TSI (total sky imager)	cloud fraction
LDIS (disdrometer)	hydrometeor size distribution, fallspeed
MET	surface meteorology, precip
RWP (1290 MHz) down for several weeks	wind profiles
ECOR	eddy correlation surface fluxes
AOS (Aerosol Observing System)	aerosol sizing and chemistry, gas chemistry
Radiosondes (120 in total)	T, q, wind profiles

Aerosol Observing System – AMF1 at **Andøya**

AOS probe	measured variables
~~ACSM (Aerosol Chemical Speciation Monitor)~~	mass concentrations of organics, sulfate, nitrate, ammonium, and chloride
CCN-200	concentration of cloud condensation nuclei at various supersaturations
$CO/N_2O/H_2O$ and O_3	gas mixing ratio sensors
CPC-3772 (fine) (Condensation Particle Counter)	concentration of sub-micron aerosol particles
UHSAS (Ultra-High Sensitivity Aerosol Spectrometer)	concentration and size distribution of sub-micron aerosol particles
~~HTDMA (Humidified Tandem Differential Mobility Analyzer)~~	the rate at which aerosol particles deliquesce at increasing RH
Nephelometer	total scattering and hemispheric backscattering of aerosol, both at ambient RH and at variable controlled RH (like the HTDMA)
PSAP (Particle Soot Absorption Photometer)	change in light transmission on a filter exposed to ambient aerosol, relative to a reference filter

Ice nucleation measurements



Paul DeMott and Thomas Hill

Colorado State University

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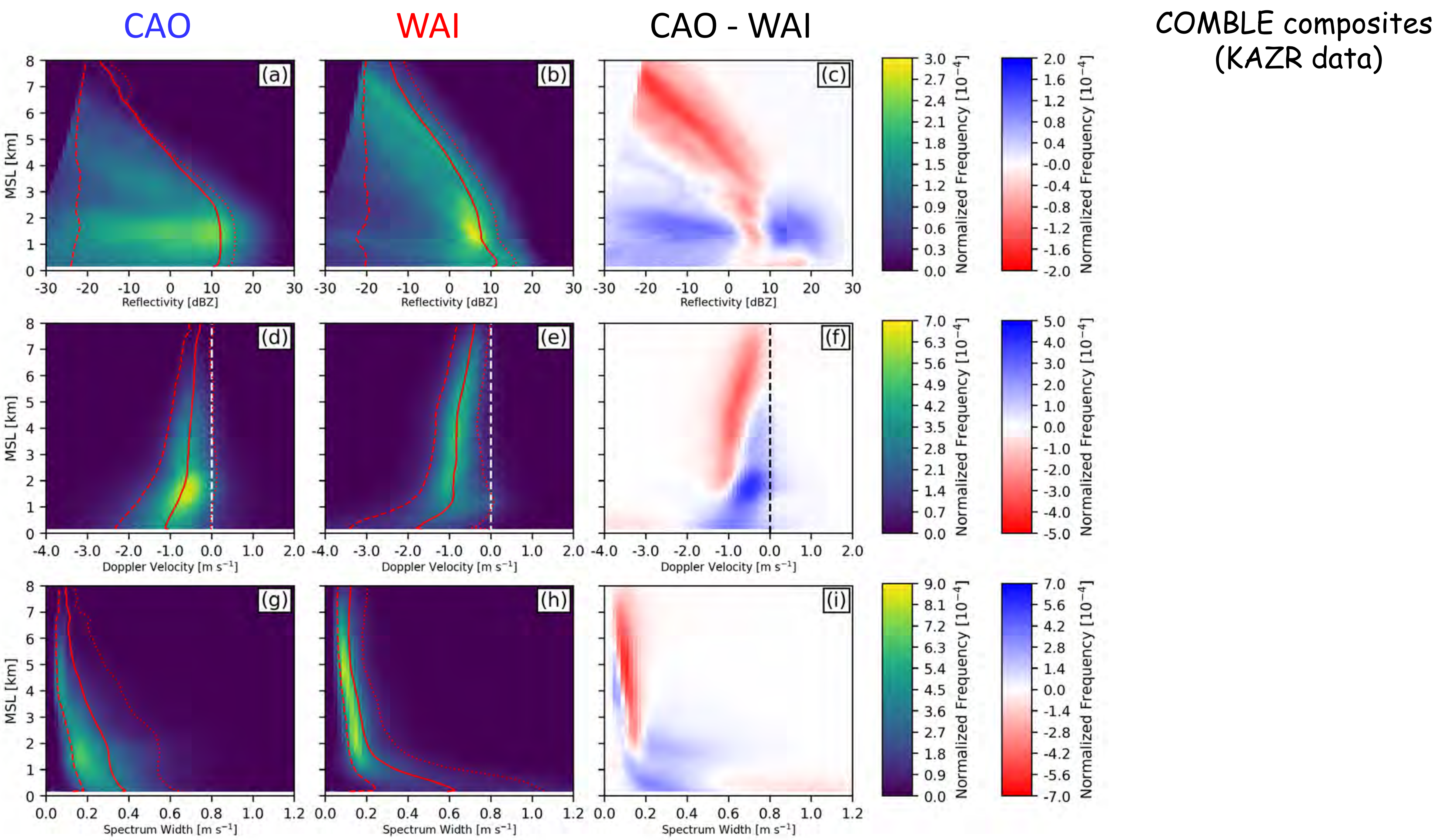
COMBLE instruments: Bjørnøya

Instrument	Measurement
MWRP	temperature and humidity profiles
MPL (profiling) + CEIL	backscatter power, aerosol layers, cloud base
TSI	cloud fraction
LDIS (disdrometer)	precip size distribution, fallspeed
MET	surface meteorology, precip
RWP (1290 MHz)	wind profiles
ECOR	eddy correlation surface fluxes
CEIL	ceilometer
DL	Doppler Lidar
sun photometer	narrow FOV radiances
VIS and IR broadband radiometer	SW and LW surface radiation budget
Radiosondes (150 in total)	T, q, wind profiles




CAO
WAI
CAO - WAI
COMBLE composites
(KAZR data)
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
MSL [km]
Reflectivity [dBZ]
Doppler Velocity [m s^{-1}]
Spectrum Width [m s^{-1}]
Normalized Frequency [10^{-4}]

Fetch-dependent CAO cloud macrostructure

Cloud Streets

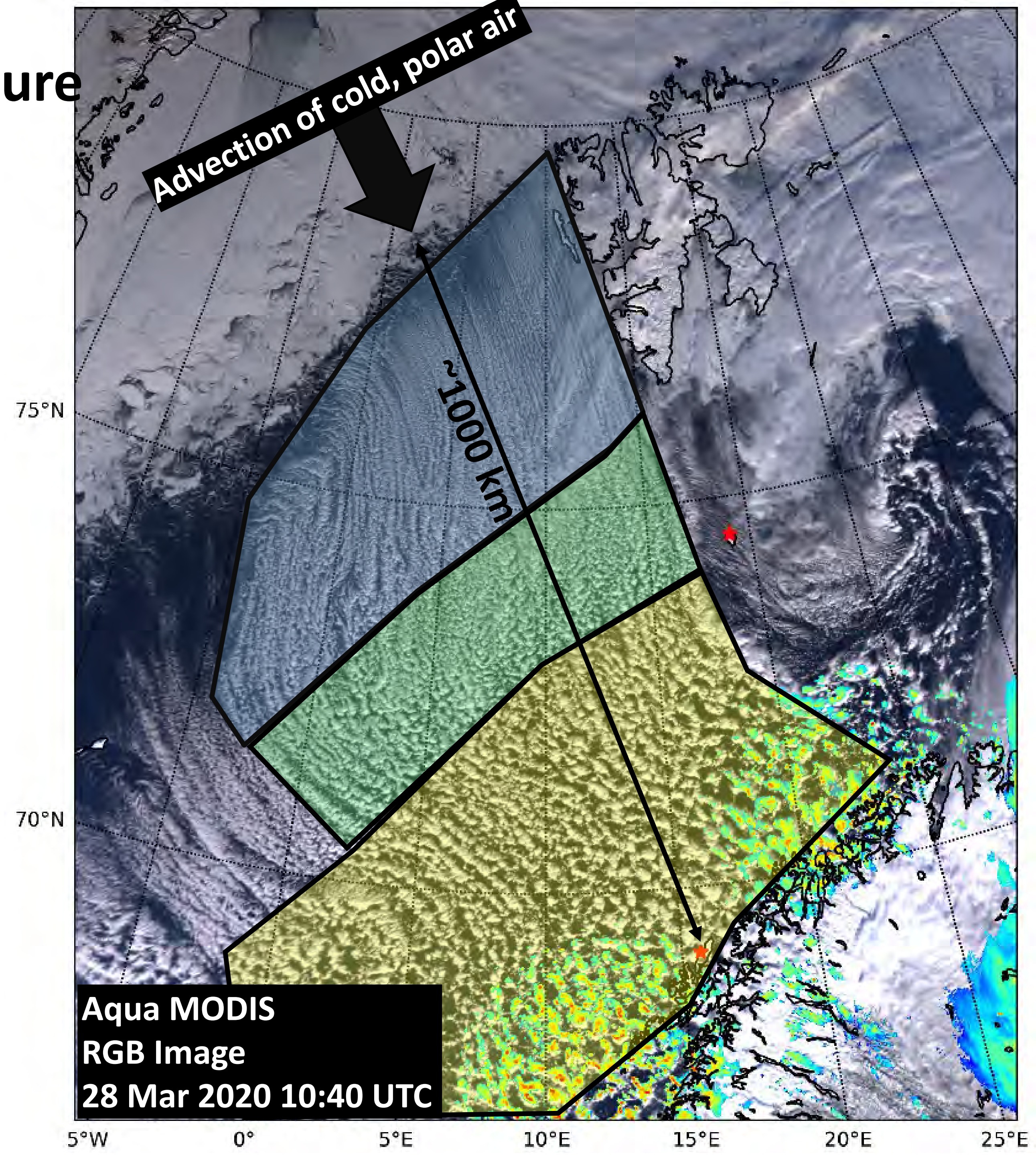
- Small convective cells are linearly organized along the wind direction due to shear-aligned helical rolls
- Surface heat fluxes, shear, and moist convection **deepen the CBL with increasing fetch**

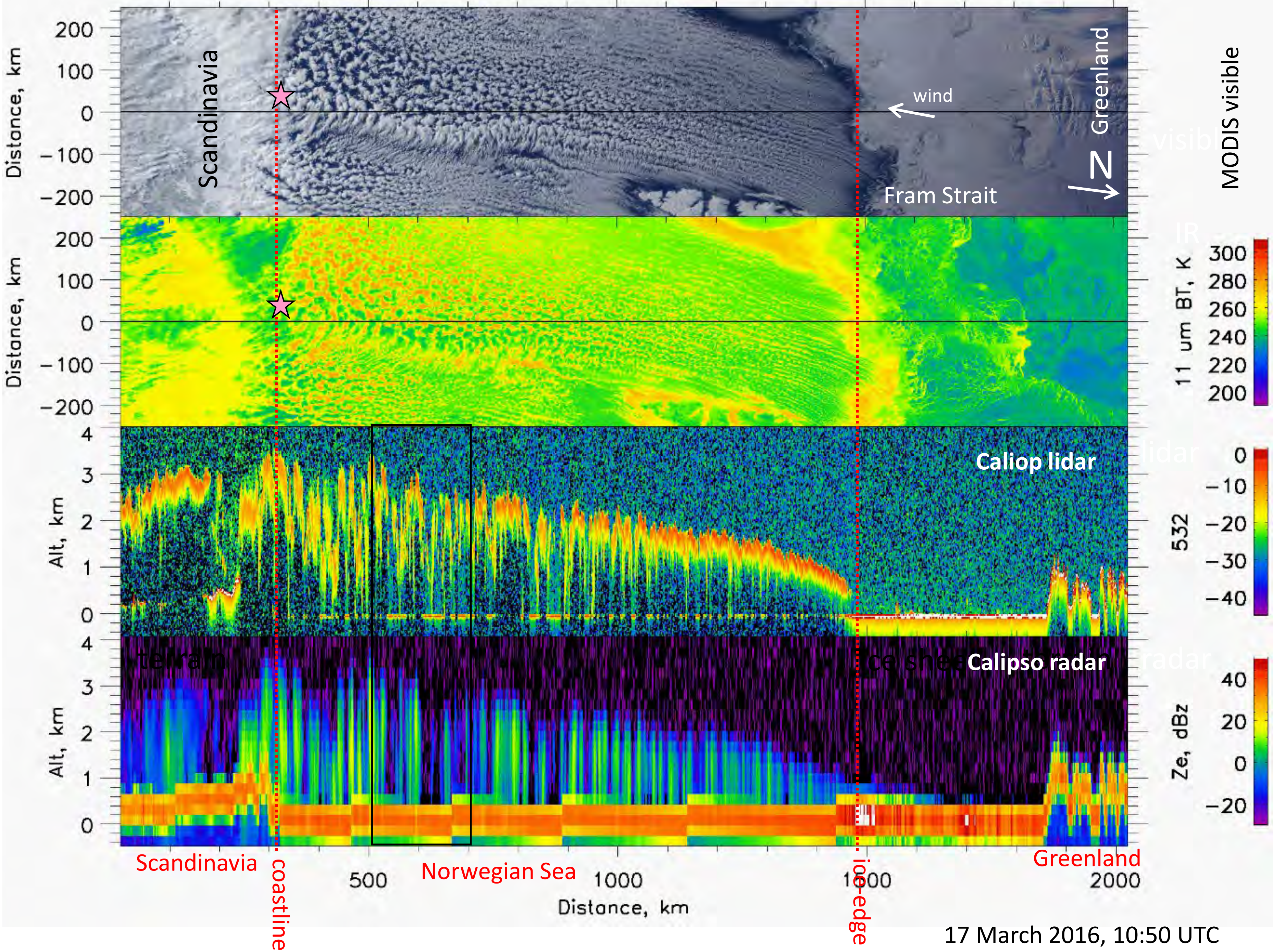
Transition region

- Microphysical and dynamical processes lead to change of cloud regime

Open cellular clouds

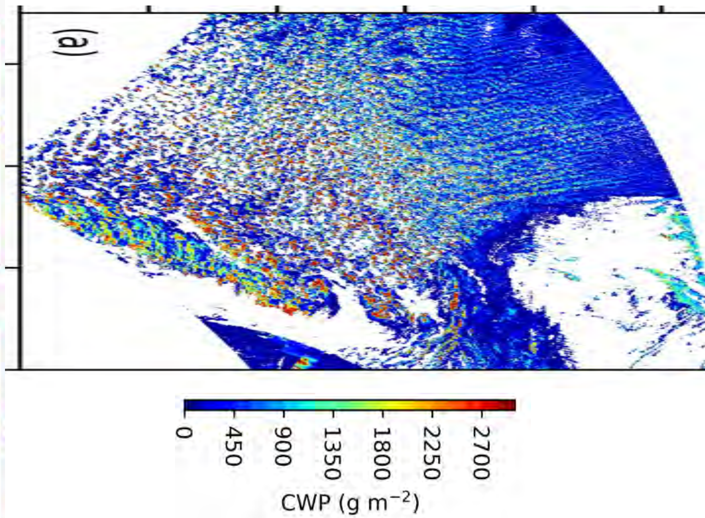
- Convective processes in cells deeper than the PBL result in pockets of heavy precipitation and large cloud free areas between the cells





17 March 2016, 10:50 UTC

13 March 2020, 950 UTC



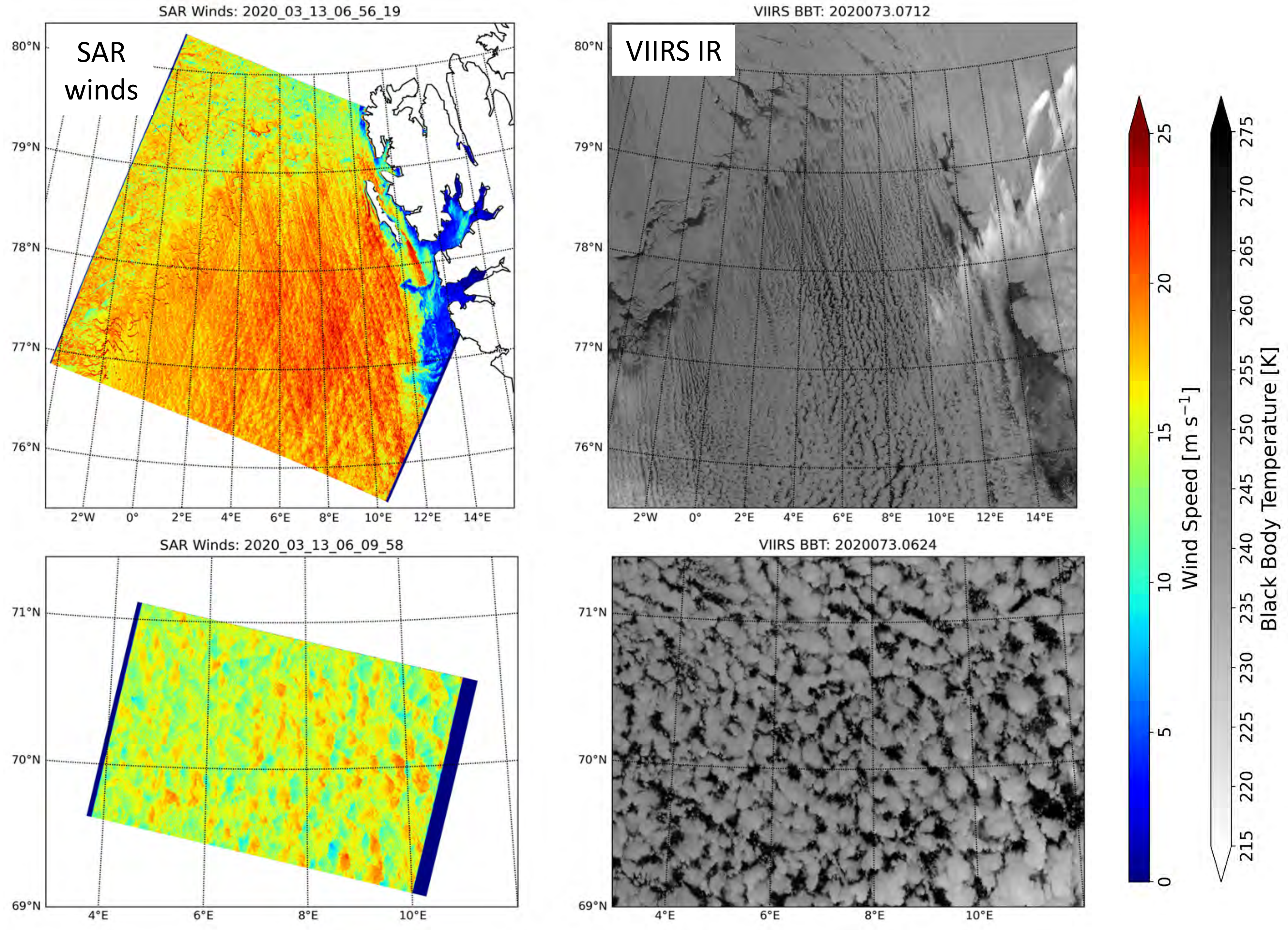
MODIS cloud water path

High-resolution SAR surface winds over ocean

cloud street region

open cell region

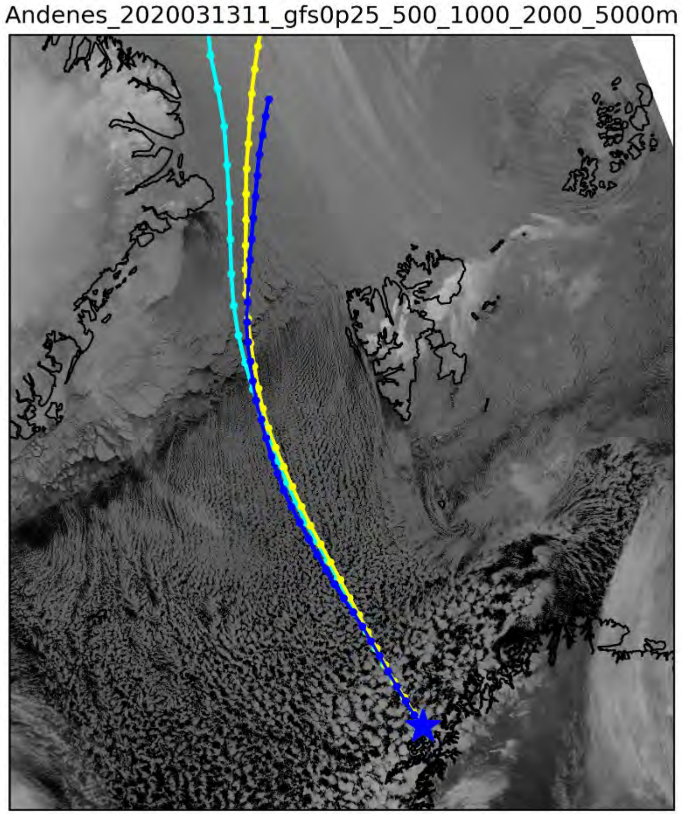
13 March 2020, 6-7 UTC

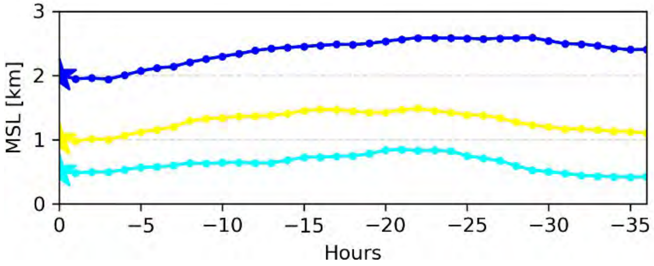


Cloud macrostructure

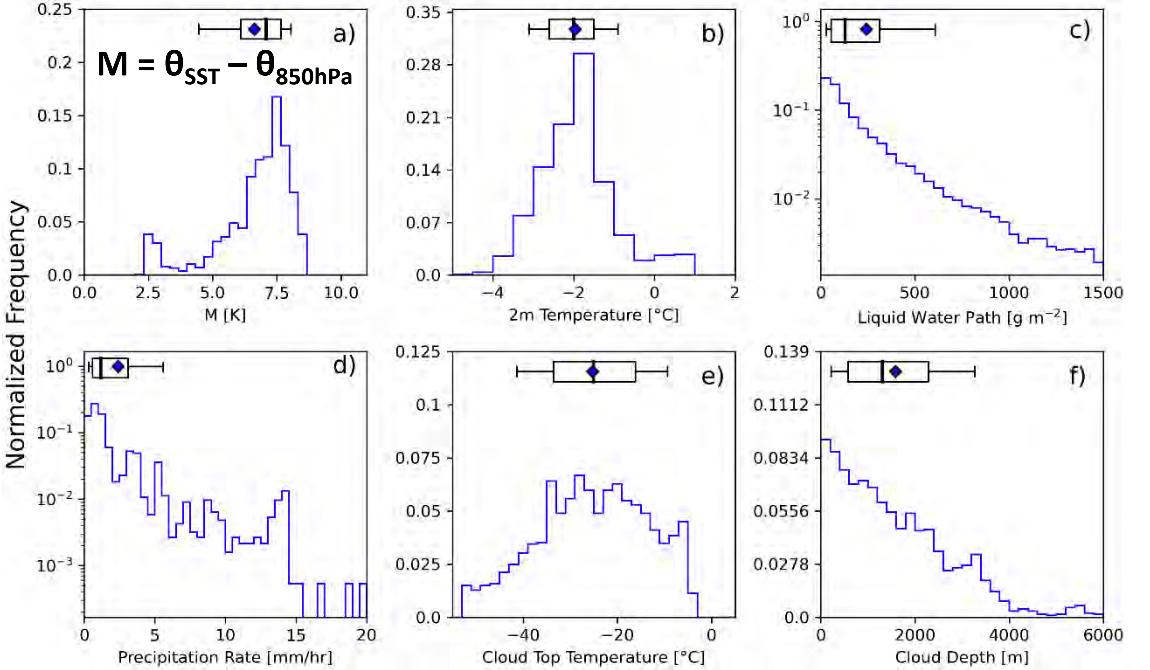
- Two intense and long-lasting CAO events were observed during COMBLE, **12-13 March and 28-29 March 2020 cases**
- Air originates from Fram Strait in both cases
- $\overline{M}$ = 7 K | $\overline{T}$ = -2 °C | $\bar{u}$ = 20 kts from NW
- 4-5 km deep convective cells at Andenes
- Many cloud tops above -40°C, yet frequent pockets of high LWP

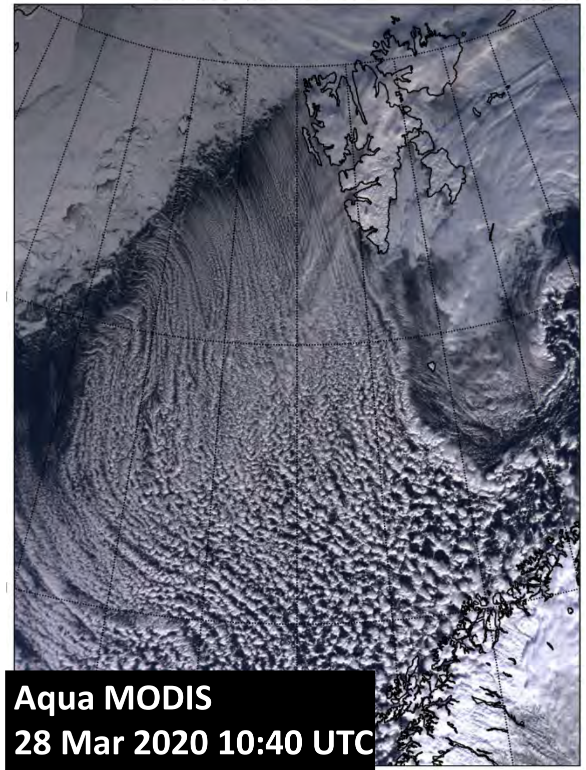
Aqua MODIS
13 Mar 2020 9:50 UTC

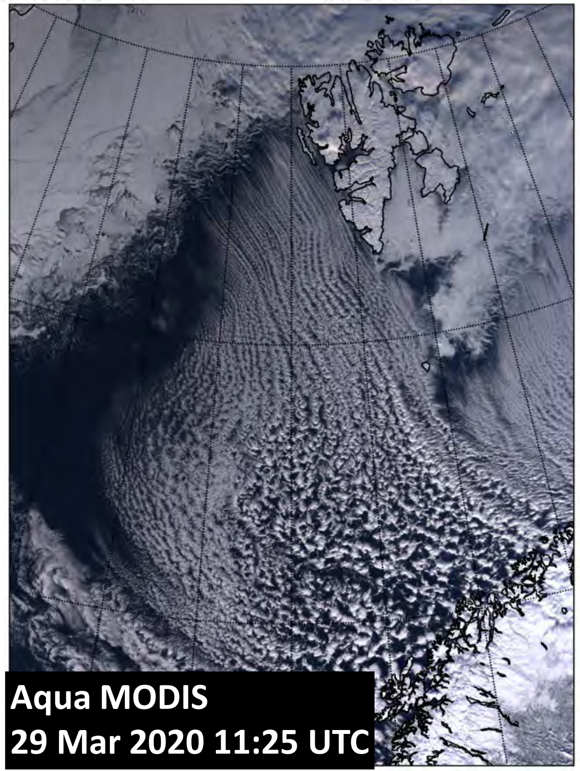




Distribution of key parameters during the 2 intense CAOs at Andenes



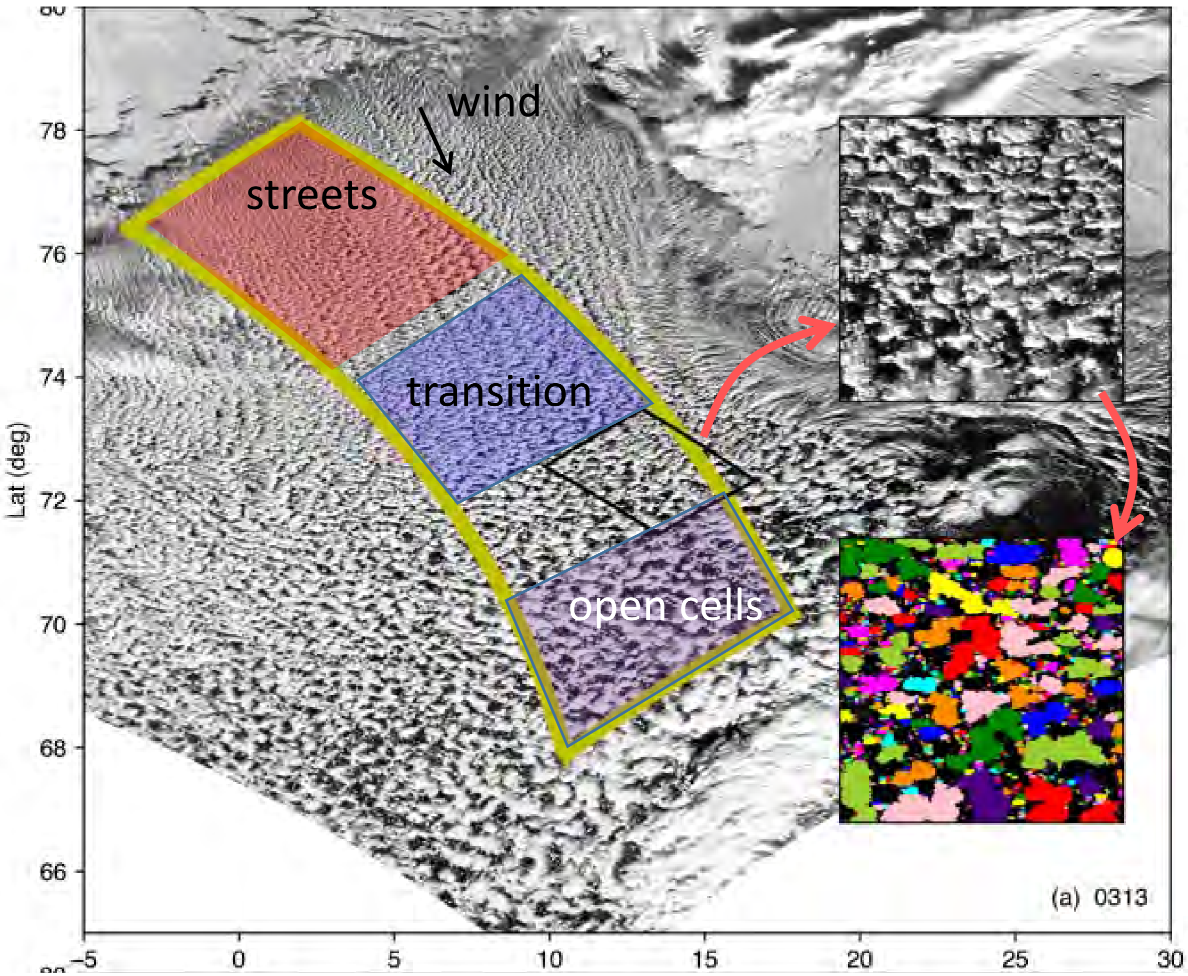


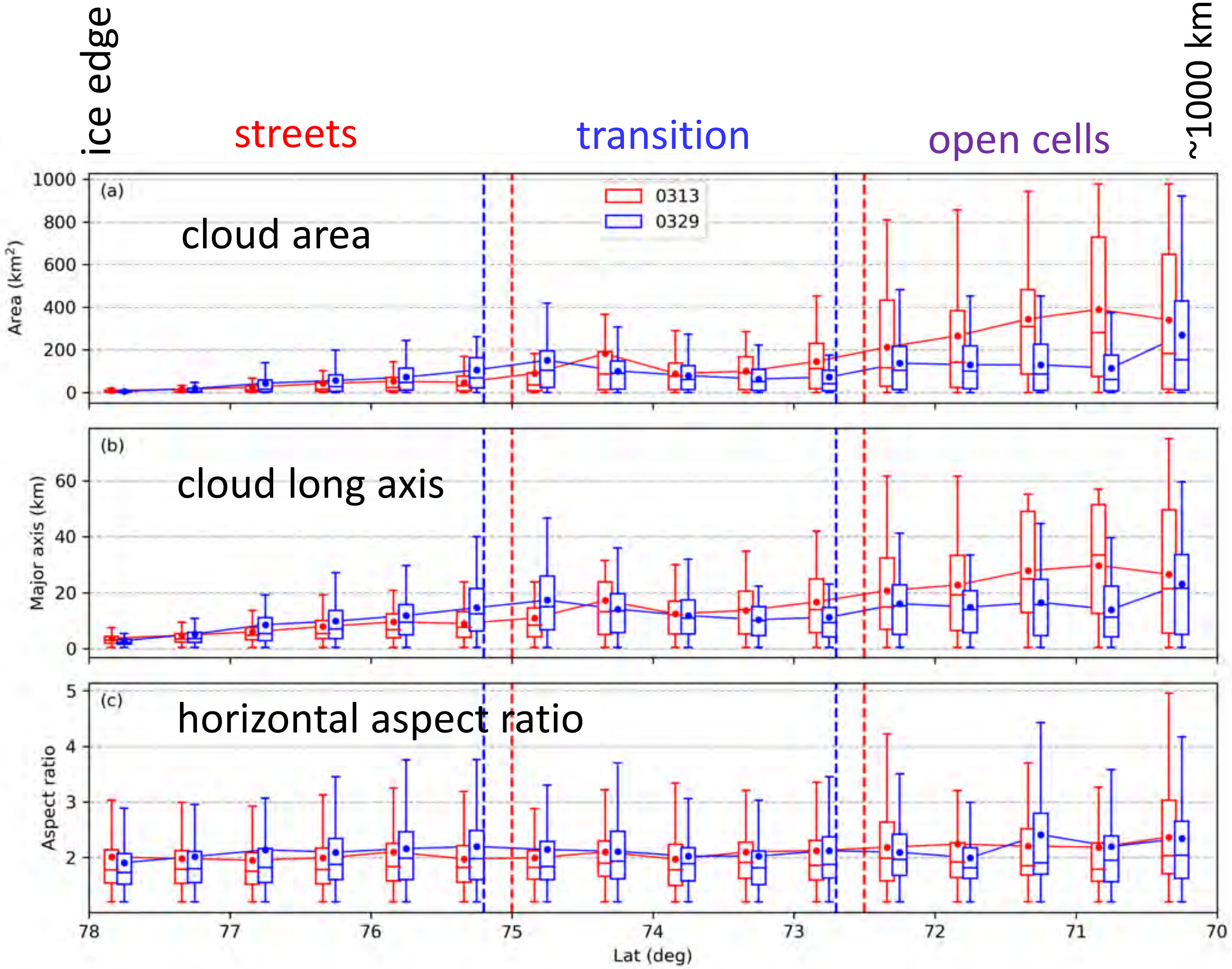


Transition from linear to open cellular cloud regime

An object identification method was used to define cloud objects from MODIS imagery, and the changes in object characteristics with fetch are studied.

The **horizontal aspect ratio** is defined as *long:short* axis of the object's enveloping ellipse.



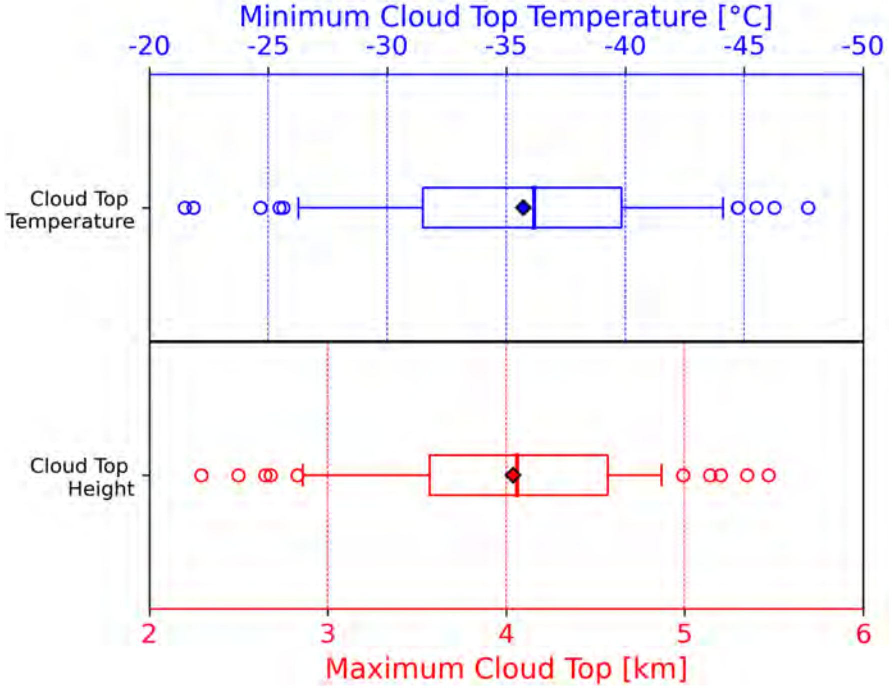


12-13 and 28-29 March 2020 cases

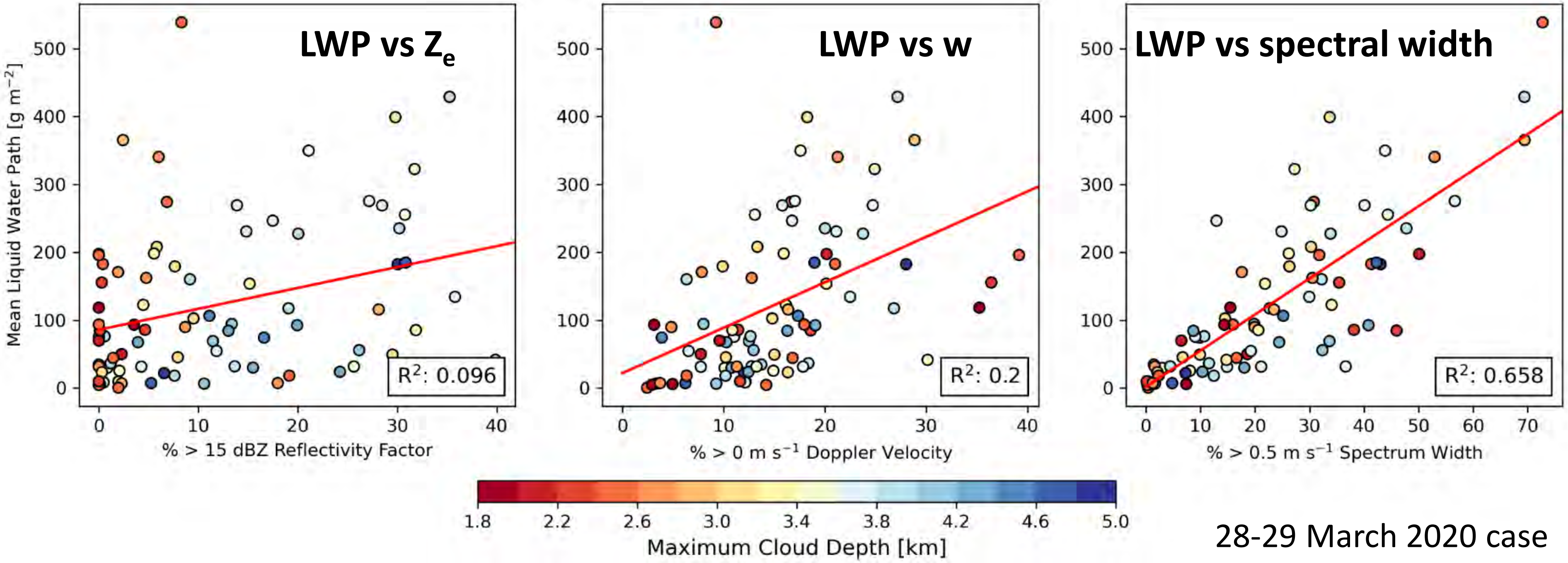
[Wu and Ovchinnikov 2022]

Properties of isolated convective cells

- ~50% of cloud tops exceed 3.5 km with ~5% exceeding 5 km
- ~50 % of the cells have CTTs below -37 °C
- Cells objectively isolated in KAZR time-height transects using a technique that can be applied to model output using radar simulators
- Further characterization and classification of these cloud cells is currently explored (e.g., Self-Organizing Maps)



Correlation of radar variables with radiometer LWP

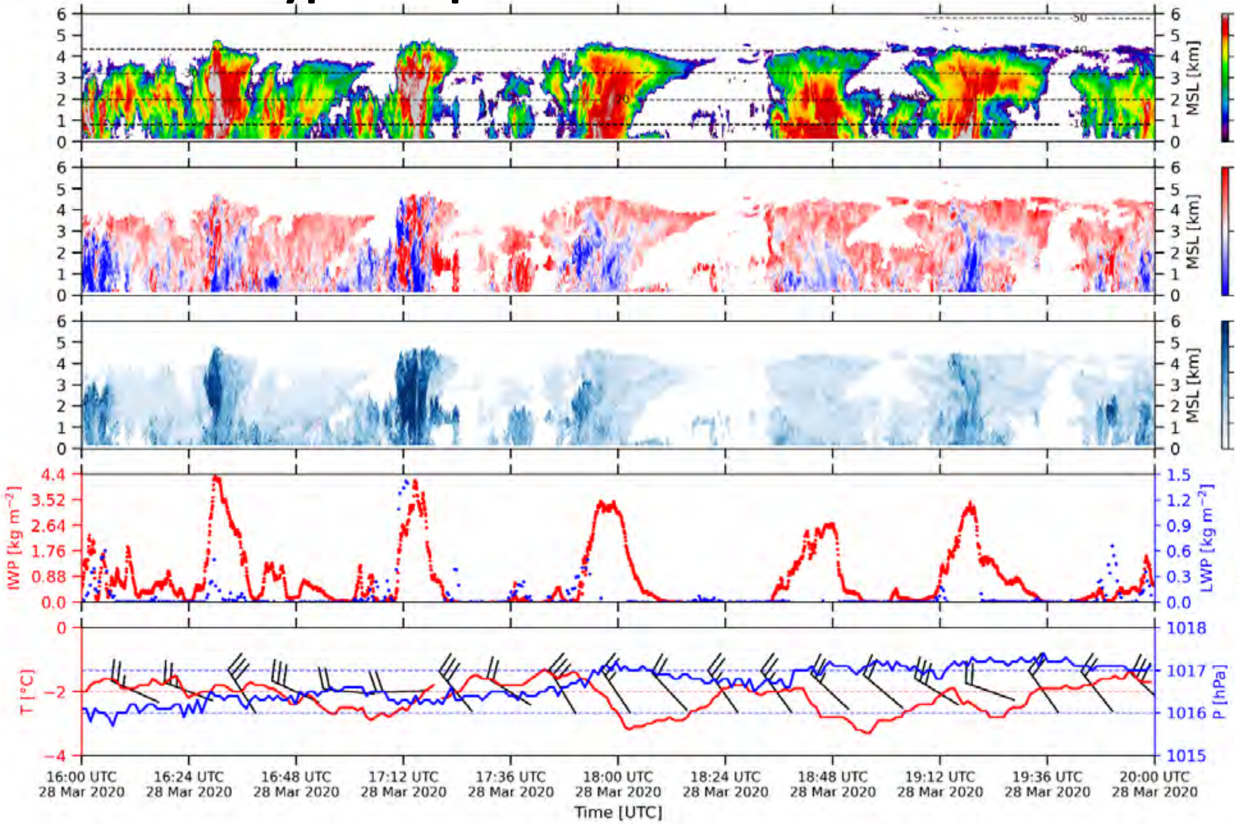


Lackner et al. 2022

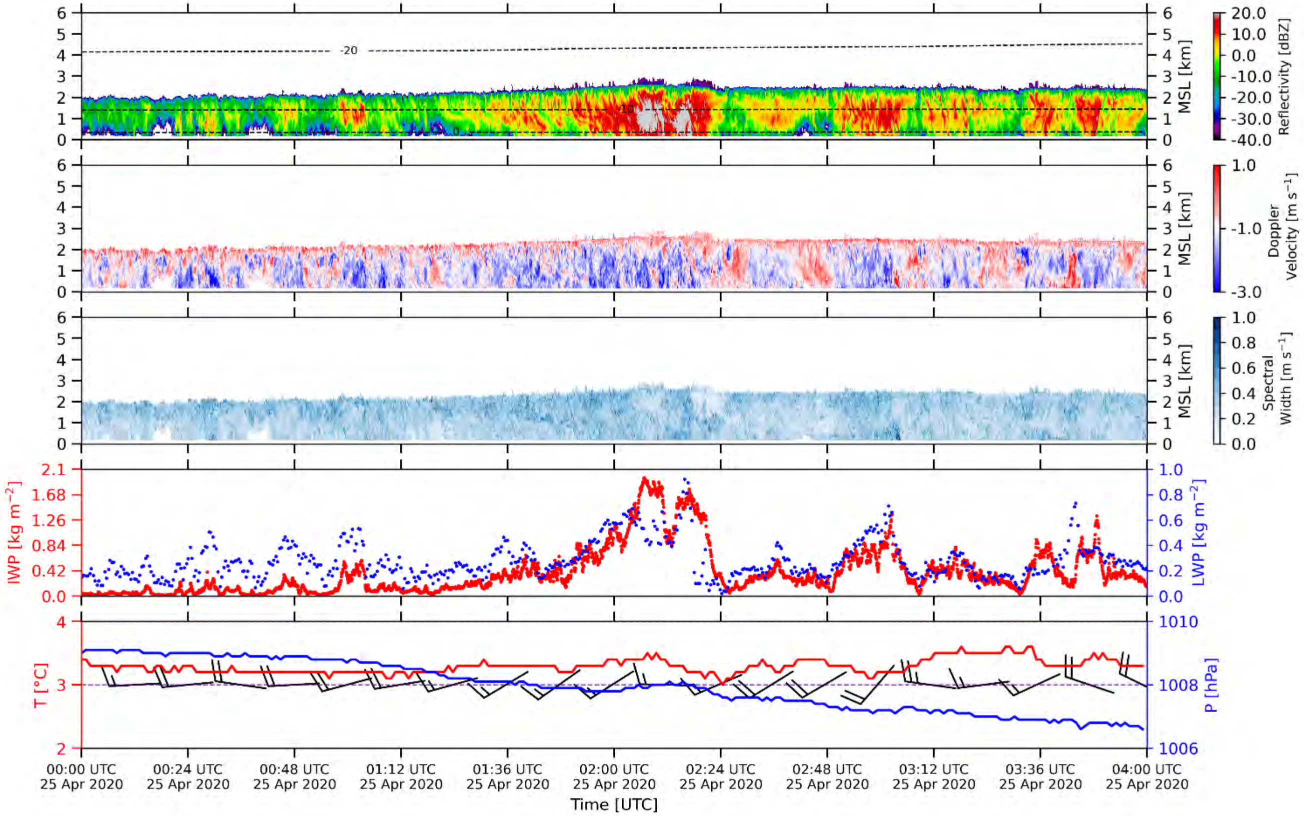
28-29 March 2020 case

Shallow closed cells sometimes occur during CAOs at Andenes

typical open cell vertical structure



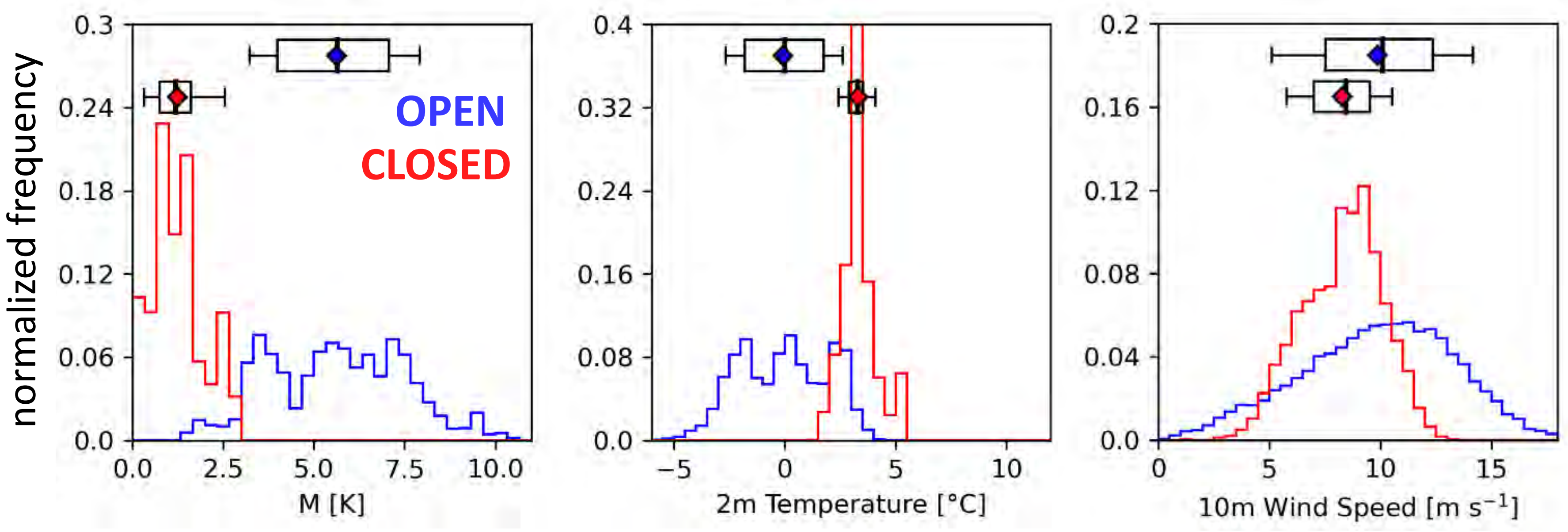
typical closed cell vertical structure



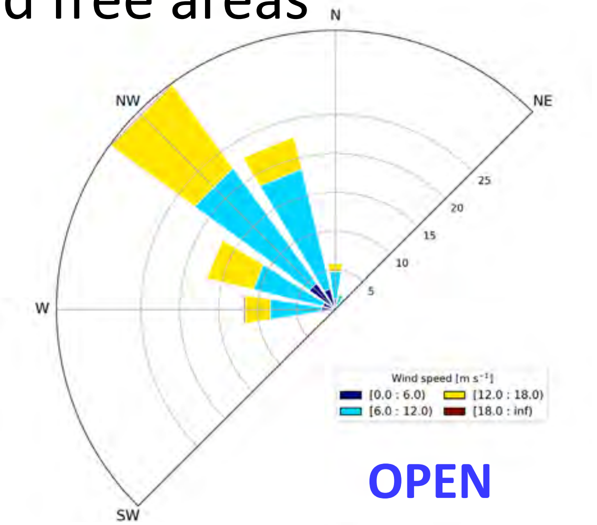
Lackner et al. 2022

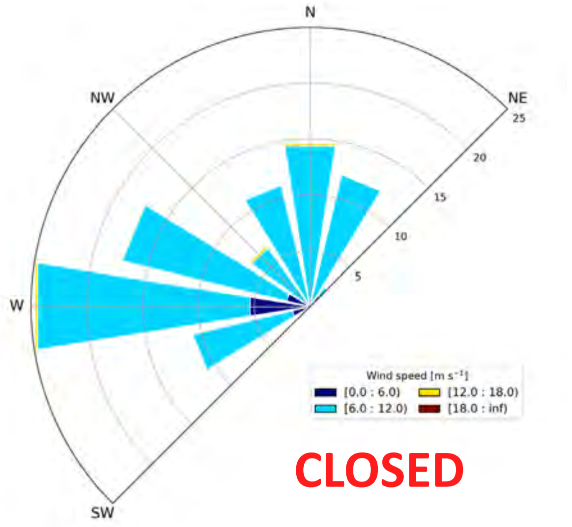
Open vs closed shallow convection: the environment

- **Open cells**: Discernible individual clouds separated by large cloud free areas
- **Closed Cells**: Relatively uniform cloud top heights with insignificant cloud free areas
- frequency at Andenes: OPEN: 72% CLOSED: 17%



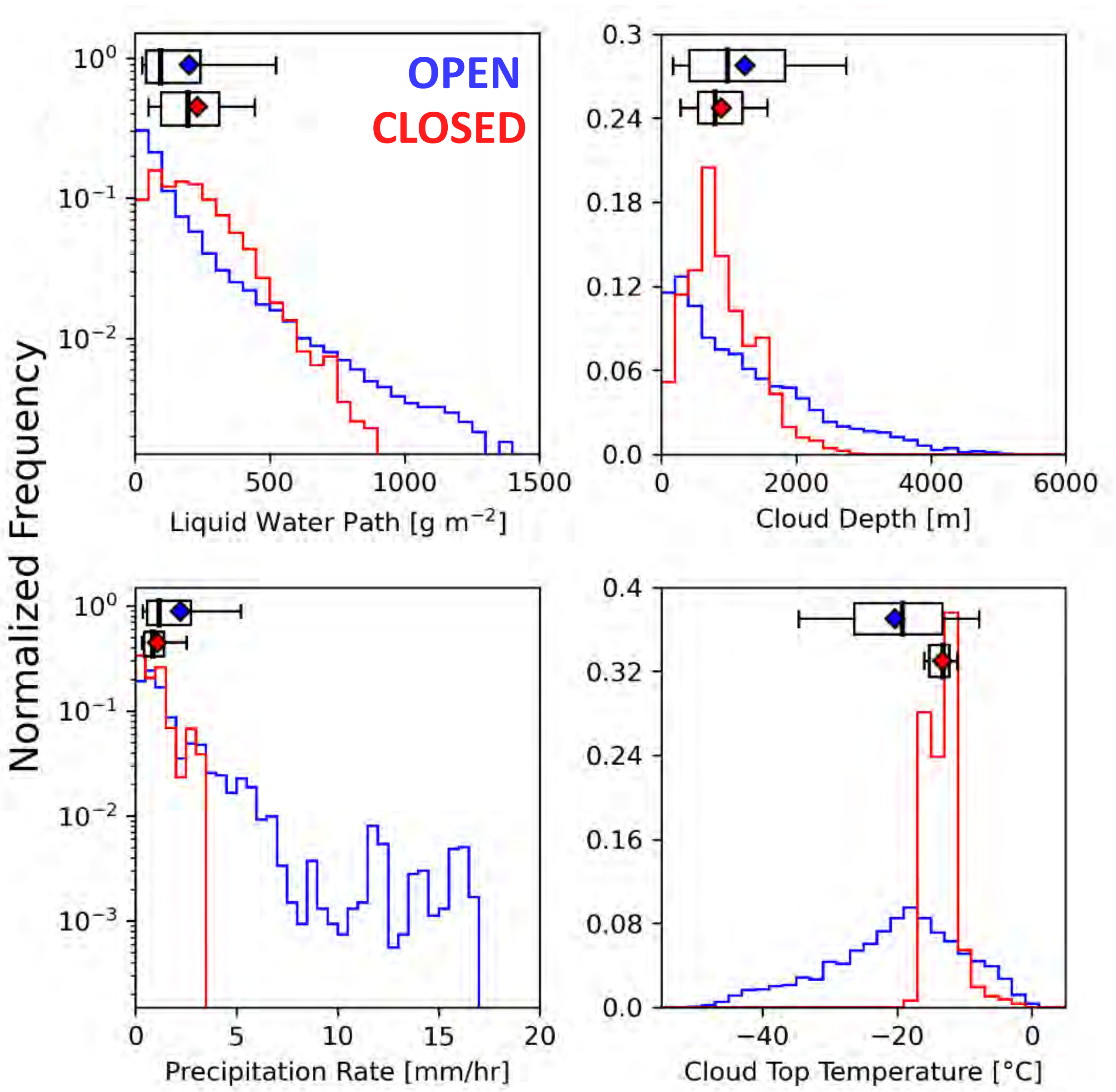
$$M = \theta_{SST} - \theta_{850\,hPa}$$





Lackner et al. 2022

Open vs closed shallow convection: cloud properties



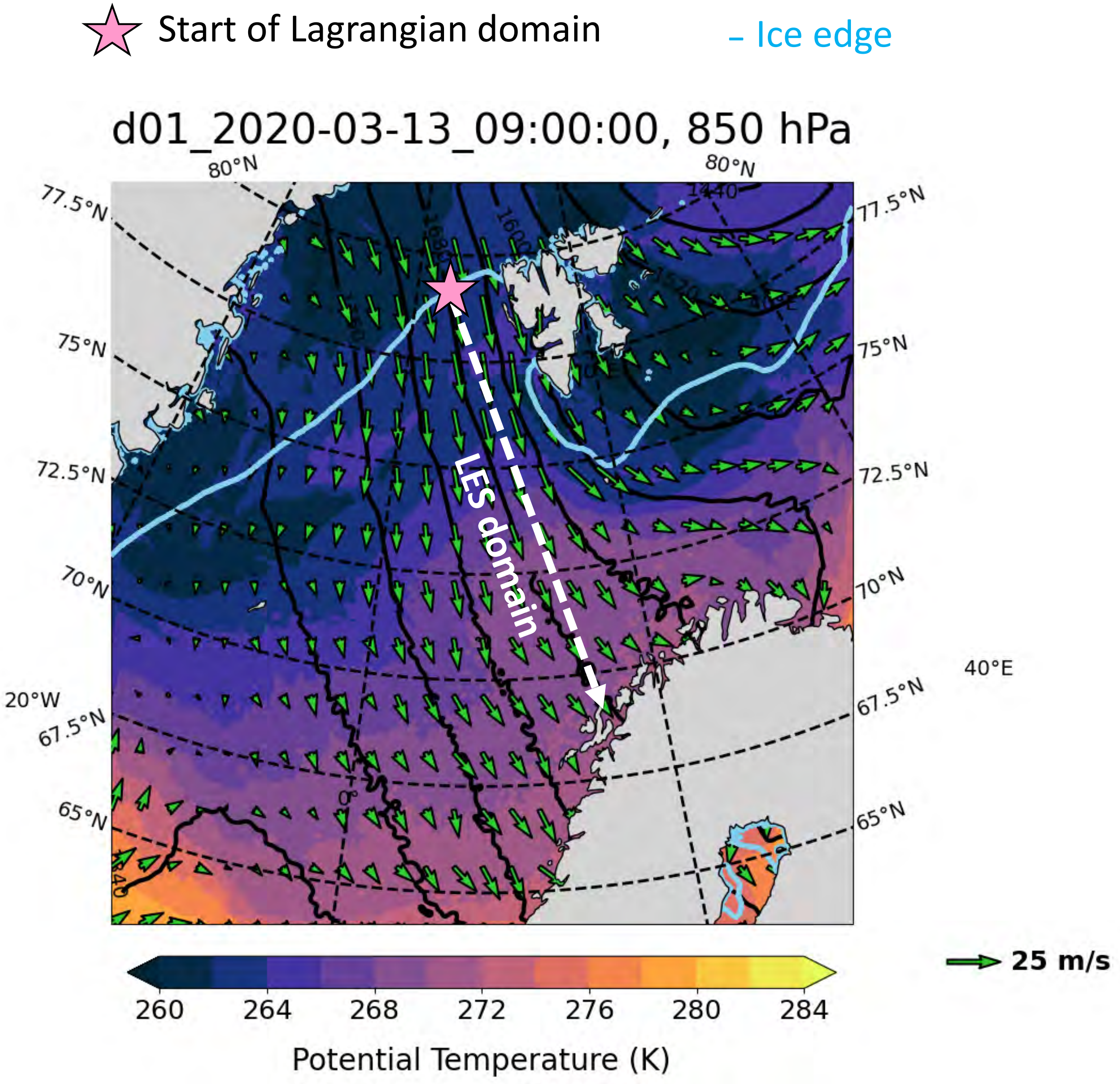
Lackner et al. 2022

Numerical simulations: Lagrangian large-eddy simulation (LES) approach

Objective: explore mesoscale organization and related spectral properties

- **WRF-LASSO model** (Gustafson et al. 2020):
- Lagrangian perspective: following BL flow computed along ERA5 trajectory
- Hourly skin temp. forcing from ERA5 to represent “moving” domain (Galilean transformation)
- Large-scale pressure gradient forcing constant in time
- 18 h simulation starting 13 Mar. 00 UTC (ice edge to Andenes)
- **Key physics:**
- Morrison MP w/ N_d=20 cc^{-1}
- RRMTG radiation and revised MM5 surface layer physics
- 3D Deardorff TKE SGS model

	nested domains
BC	periodic outer domain
Δx=Δy	90 / 30 m
Δz	30 m
domain	97x97 x 6 / 32x32 x 6 km



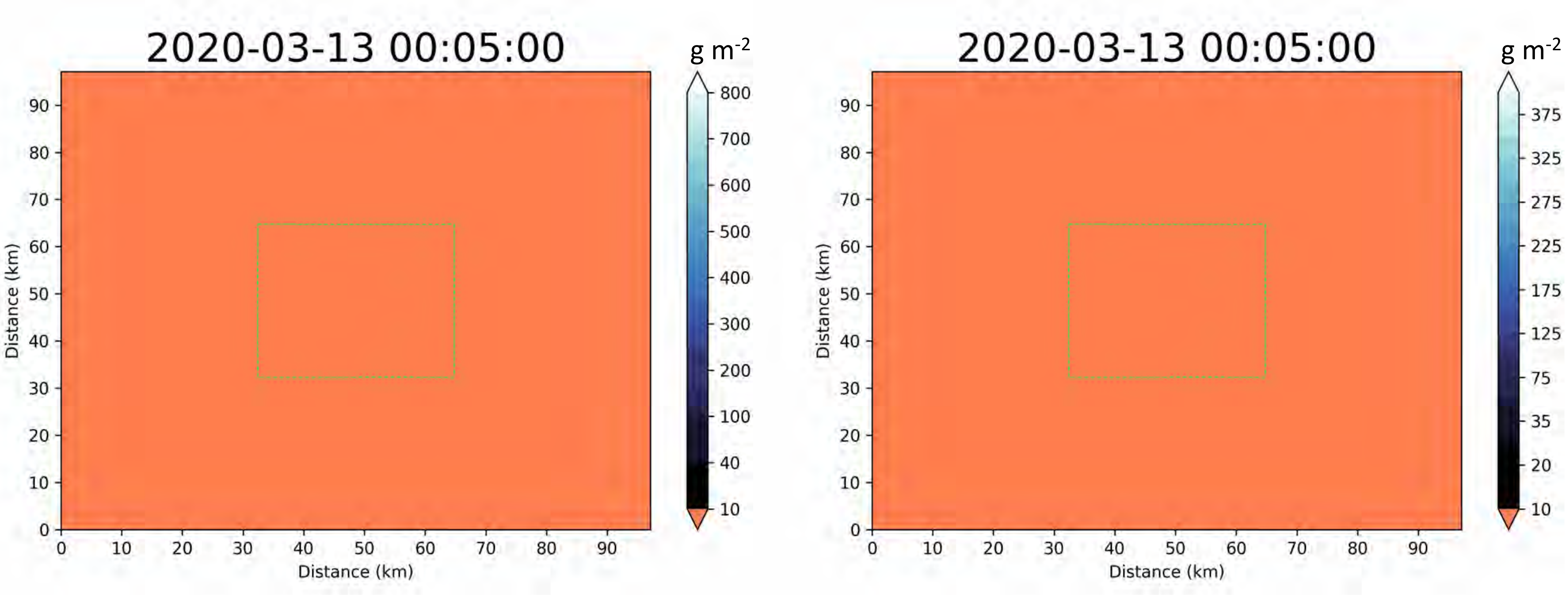
courtesy Tim Juliano

Lagrangian LES:

temporal evolution of cloud structures

ice water path

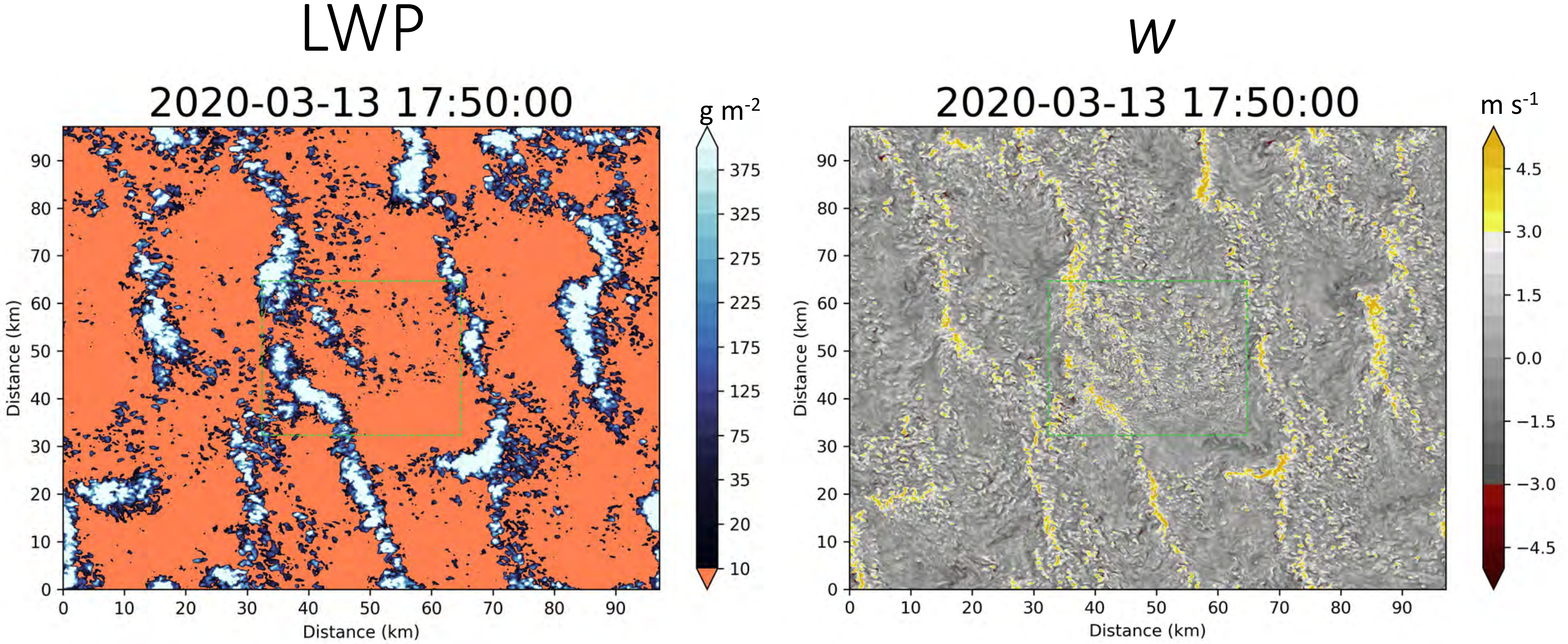
liquid water path



90 m outer domain. Inner domain shown by box

courtesy Tim Juliano

Lagrangian LES:
strong updraft regions correlate with high LWP



Cells size ~20-40 km

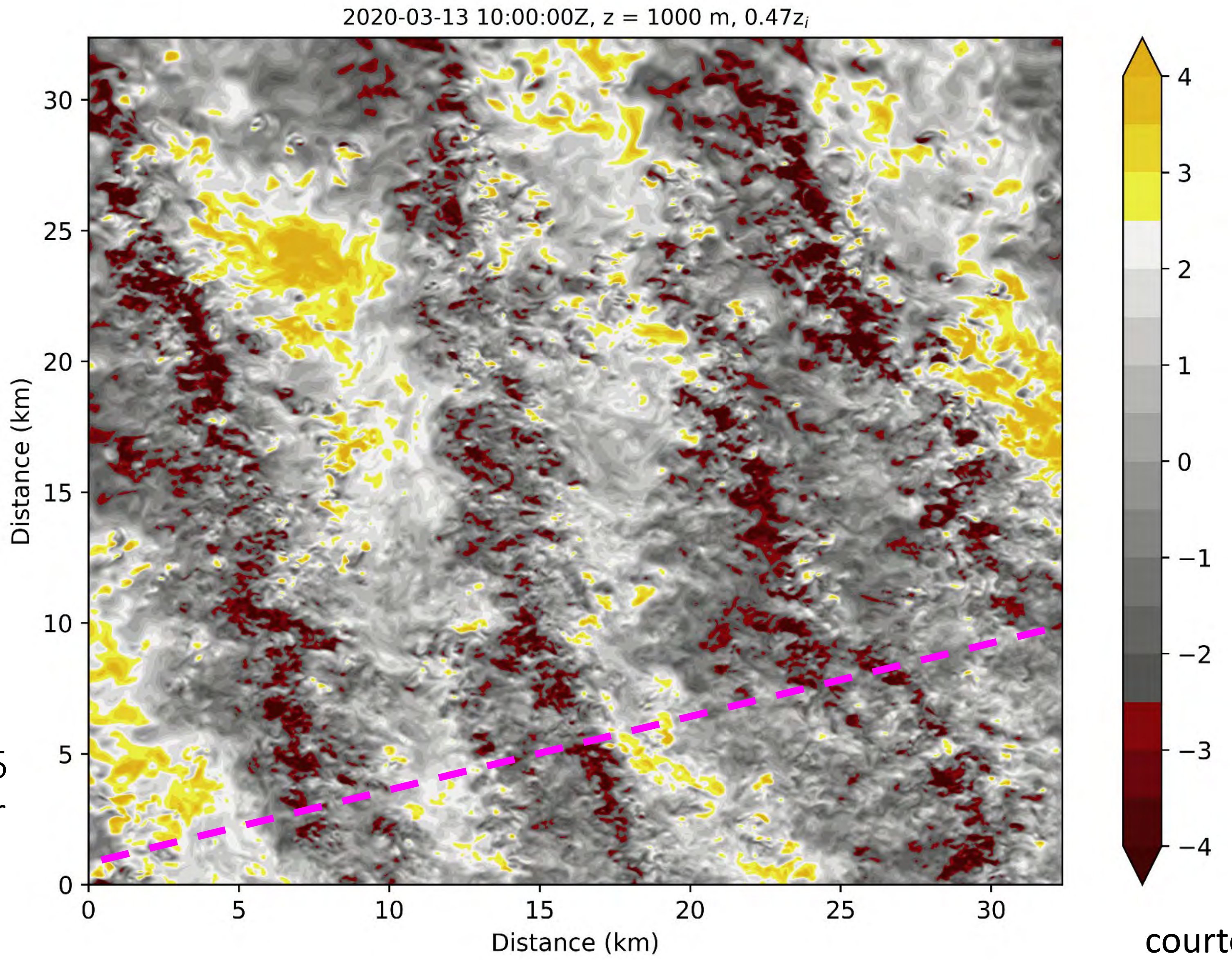
z ~ 1500 m

outer domain

courtesy Tim Juliano

Lagrangian LES

Using high-resolution model output to examine coherent structures with the Power Spectral Density (PSD) approach



U' (m/s)

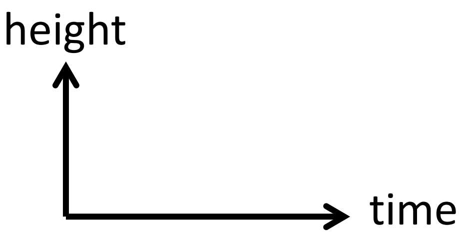
Shift transect every ~4.5 km: total of 13 PSDs per height per time

inner domain

courtesy Tim Juliano

Lagrangian LES
Temporal evolution of across-roll normalized PSD

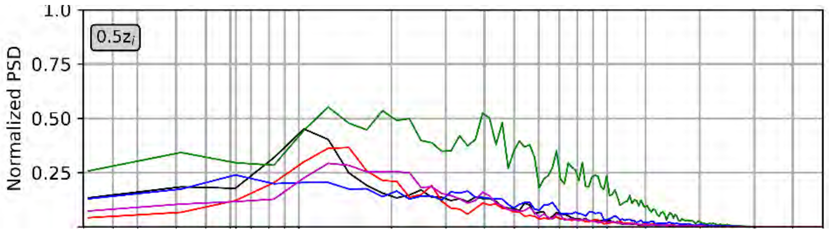
outer domain



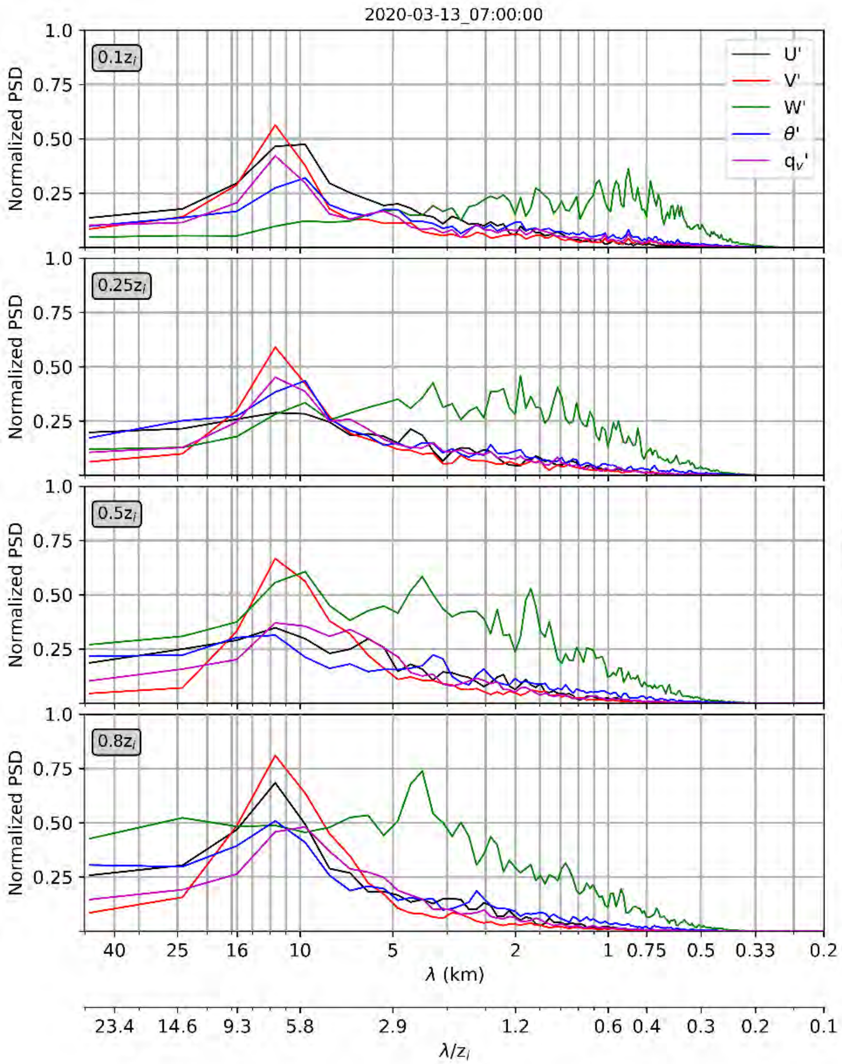
Key Takeaways:

- w’ is clear outlier: most energy-containing structures characterized by sizes much smaller than any other field examined here
- Increase in energy over time due to organization of coherent structures
- Transfer of energy from relatively smaller scales to larger scales

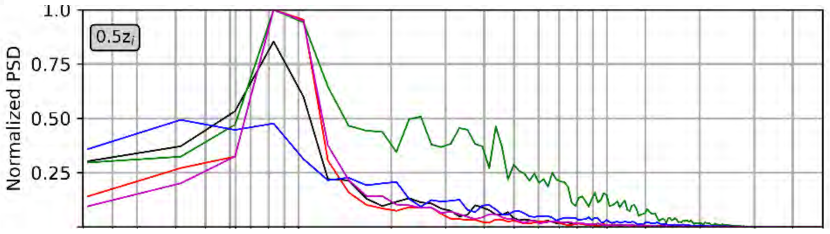
04 UTC



07 UTC



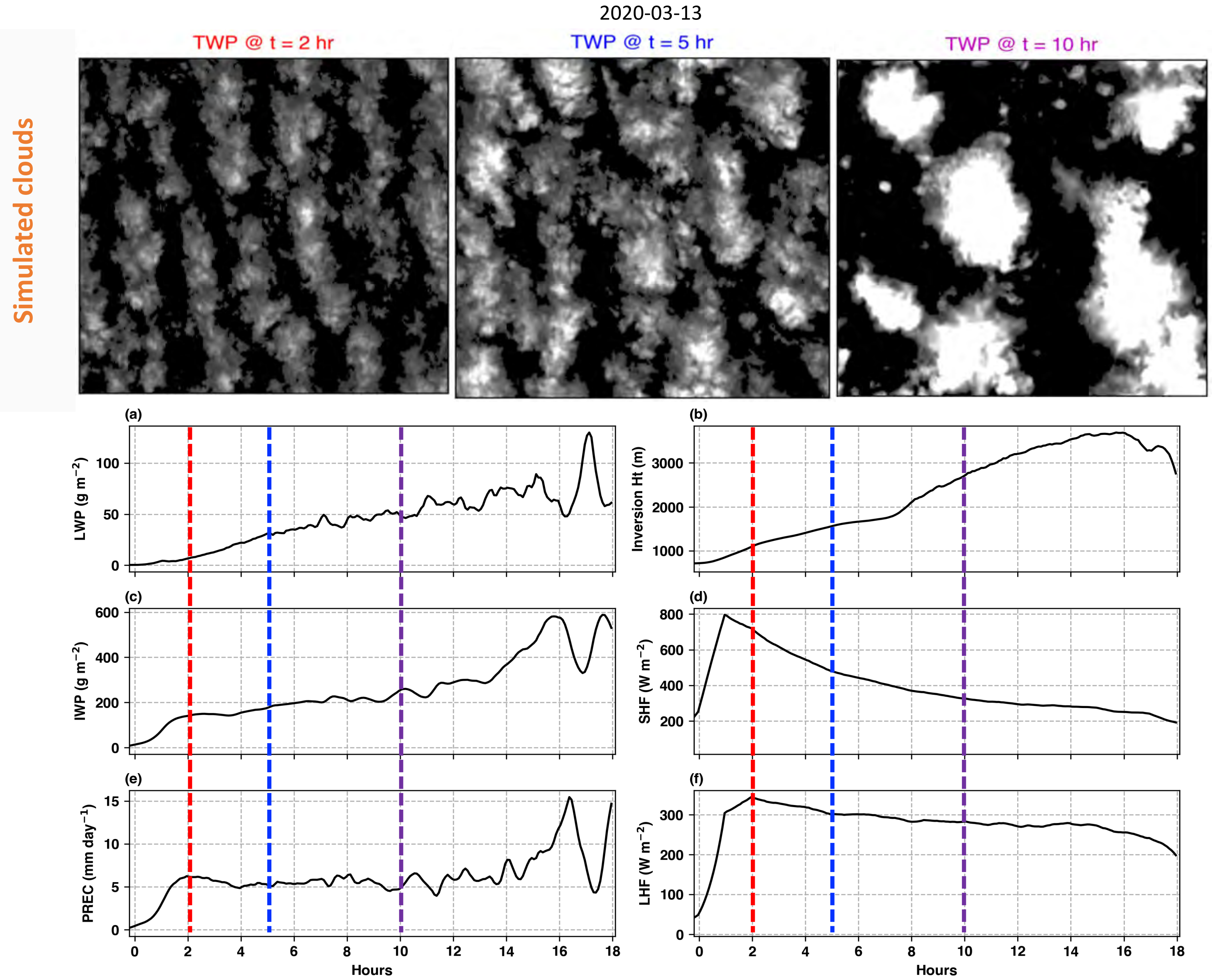
10 UTC



*Note: PSDs for each variable are normalized by maximum value across all heights and times (6 h period, Δt=10min)

courtesy Tim Juliano

Exploring the role of aerosol-cloud interactions and microphysics in CAO cloud organization:



PNNL LES using System for Atmospheric Modeling (SAM; Khairoutdinov and Randall, 2003)

focus on a *quantitative description of cloud morphology*

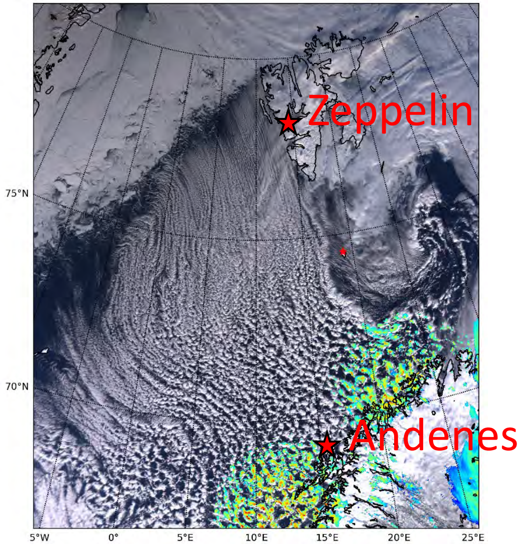
N_c=20 cc^{-1} and “MPACE condition”

Courtesy: Mikhail Ovchinnikov and Peng Wu

CAO Aerosol Particle Size Distributions

Abigail Williams, Jeramy Dedrick, Lynn Russell, Florian Tornow, Ann Fridlind, Israel Silber

- For identified CAO events, modes of observational aerosol PSD measurements are fitted at up & downstream sites



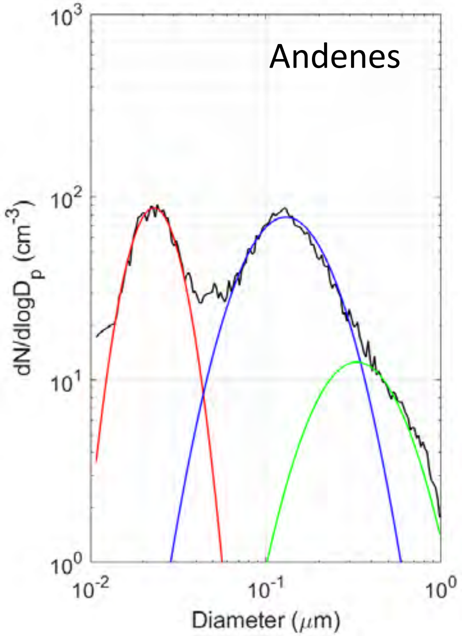


Fig 1: UHSAS and SMPS measured size distribution (black) with modal fits (red, blue, green) for 3/13

- Most cases characterized by three modes (Aitken, accumulation, coarse)
- Note the decrease in accumulation number from upstream to downstream
- Derived aerosol modal parameters suitable for use in the modeling of CAOs

Location	Case	**Mode 1 (Aitken)**			**Mode 2 (Accumulation)**			**Mode 3 (Coarse)**			**Total N**
		N (cm^{-3})	D (μm)	σ_g	N (cm^{-3})	D (μm)	σ_g	N (cm^{-3})	D (μm)	σ_g	(cm^{-3})
Zeppelin	13-Mar	38	0.03	1.8	194	0.13	2.2	24	0.61	1.9	256
	5 Case Avg	125±114	0.04±0.01	1.6±0.1	154±36	0.15±0.02	1.7±0.3	9±9	0.4±0.1	2.2±0.3	285±88
Andenes (COMBLE)	13-Mar	28	0.02	1.4	43	0.13	1.7	7	0.33	1.7	78
	5 Case Avg	21±0.001*	0.02±0.001*	1.6±0.4*	94±73	0.13±0.01	1.6±0.1	6±3	0.40±0.07	1.7±0.2	99±60

Fig 3: Derived PSD modal parameters for upstream (Zeppelin) and downstream (COMBLE – Andenes) for 3/13 and the average of five selected cases

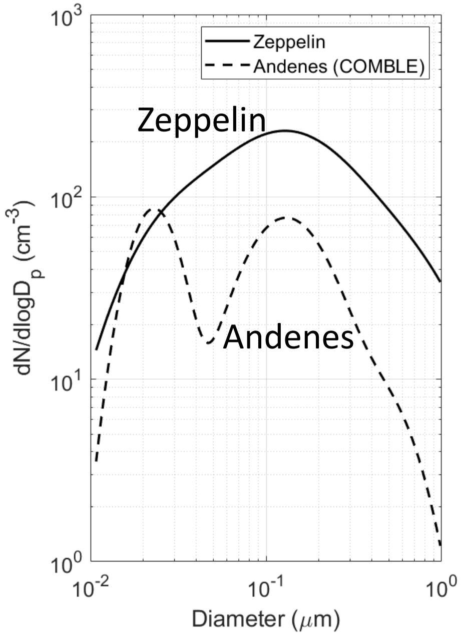
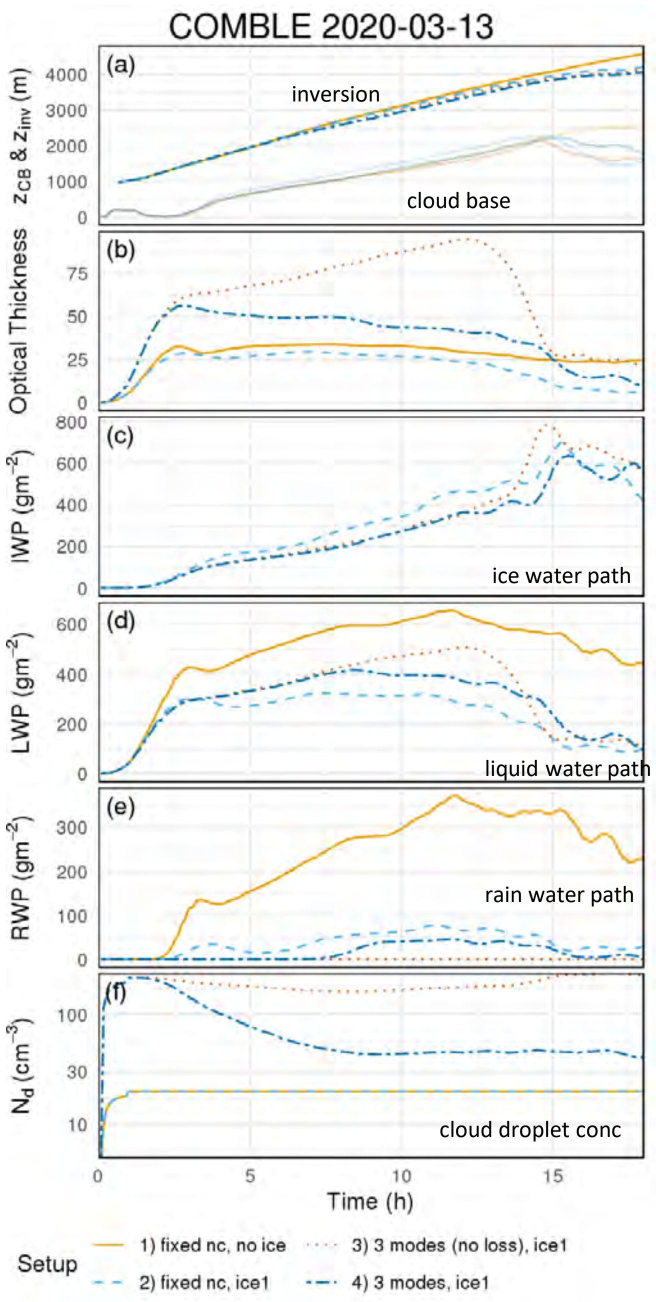


Fig 2: Fitted distributions upstream (Zeppelin) and downstream (COMBLE – Andenes) for 3/13

Exploring the role of aerosol-cloud interactions and microphysics in CAO cloud organization:



Objective: understand modal aerosol evolution and association with cloud processes during CAO Lagrangian evolution using **DHARMA LES (**Distributed Hydrodynamic-Aerosol-Radiation Model Application; Ackerman et al. 2000, Stevens et al. 2002)

Results quantify the importance of a prognostic aerosol (CCN and INP) treatment:

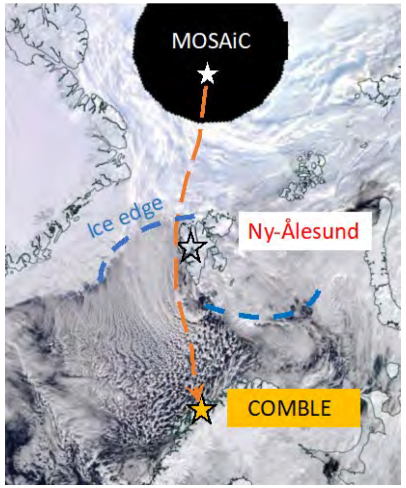
- Inclusion of frozen hydrometeors greatly reduces LWP and rain, in particular beyond ~15 h where cloud-top experiences homogeneous freezing and rapid glaciation
- **Balance of aerosol loss** (consumption via precipitation formation and riming) **and sources** (sea spray emissions and FT entrainment) **leads to a quasi-steady low-N_c state after ~8 h**
- **Fixing N_c near the low quasi-steady value** generally shows **~50 % smaller optical thickness**
- **Fixing modal aerosol without loss** omits rain formation and leads to **100 % greater peak optical depth** compared against simulation that allows loss

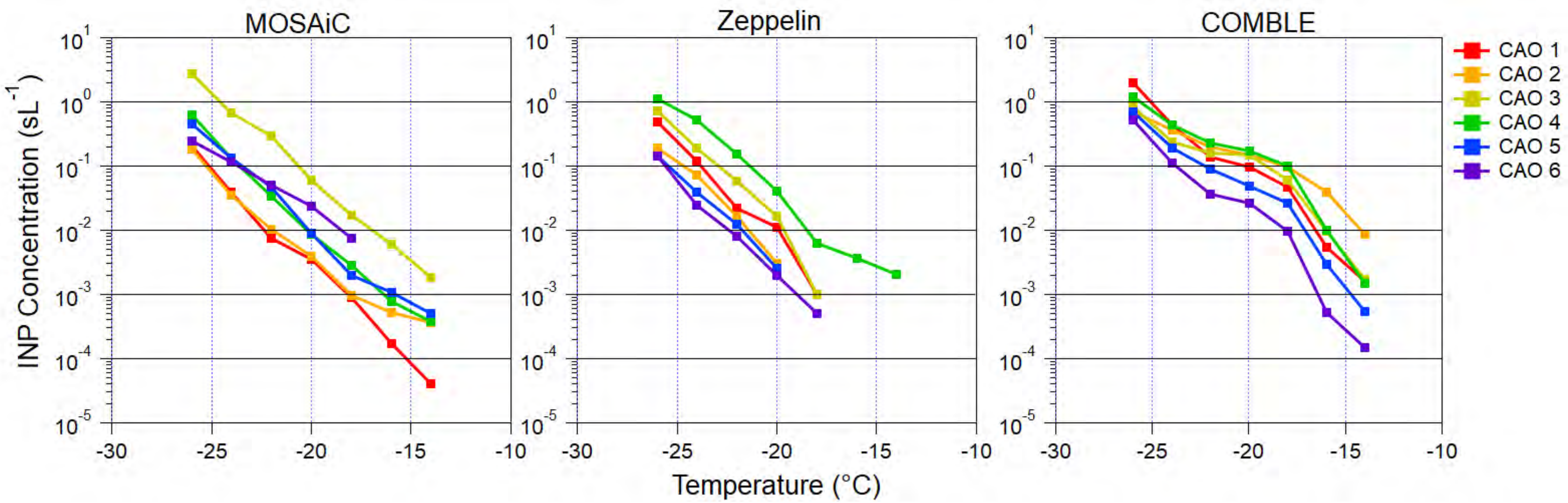
Next steps:

- Develop **prognostic immersion-mode N_{inp}** reliant on coincident aerosol properties (instead of current diagnostic N_{inp}) and compare predicted INP spectra with observations
- Repeat **comparisons with satellite and COMBLE observations** (lidar and radar variables, LWP, soundings; morphology analysis from passive satellite measurements)

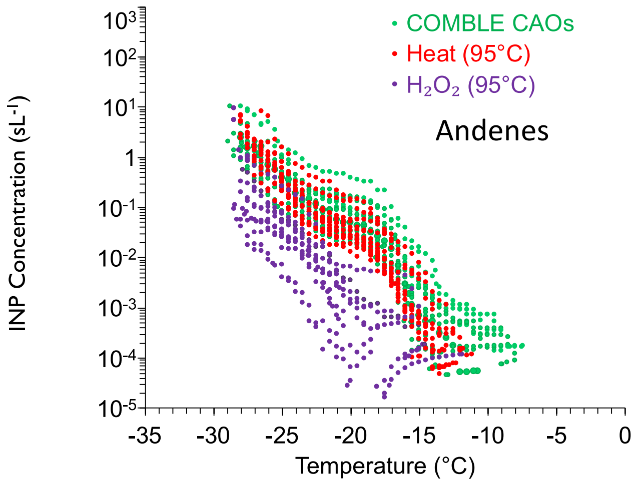
Courtesy: Florian Tornow, Ann Fridlind, Israel Silber, Lynn Russell, Jeramy Dedrick, Abigail Williams

INPs during cold air outbreaks: unique character; source as being from the ocean or mixing from the free troposphere is still under investigation

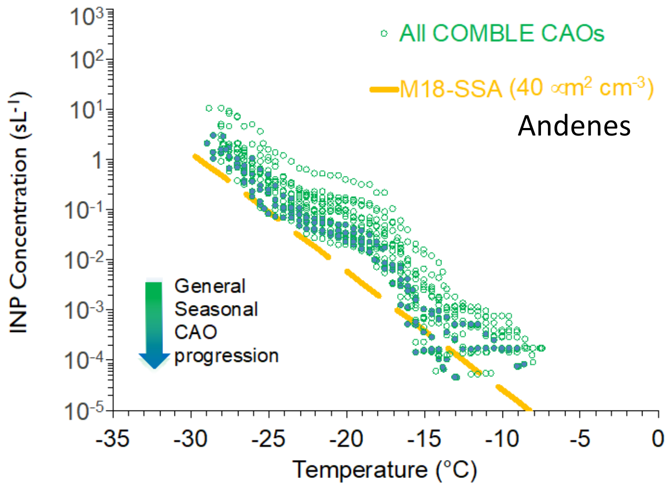




Marked differences in COMBLE versus upstream INPs for December to March (1-6) CAO events



INPs in CAOs have modest bio-INP influences, but are highly organic (possible sea spray, soil or biomass burning sources)



An existing sea spray INP parameterization (M18) for North Atlantic cannot describe INPs

courtesy Paul DeMott

Upcoming COMBLE LES/SCM Model Intercomparison

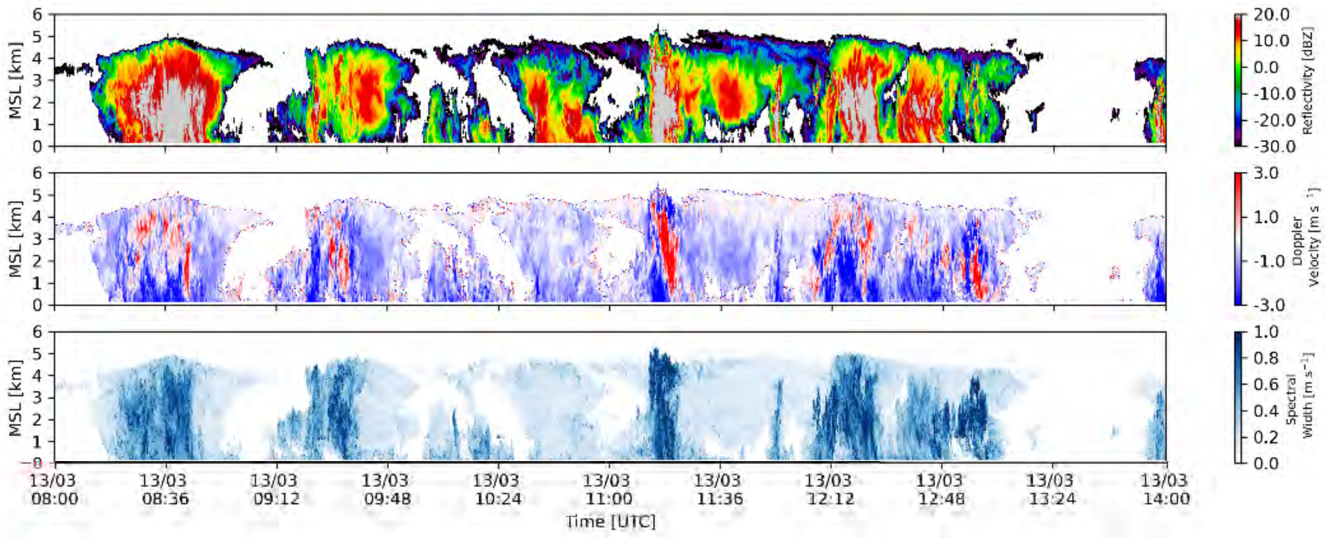
Main topics: (a) simulated mesoscale cloud organization; (b) evolution of cloud properties/vertical structure; (c) role of aerosol and precip. in controlling cloud transitions

13 March 2020 COMBLE CAO case selected:
(1) Setup developed based on community input
(2) Python Notebooks provided to participants to reduce commitment
(3) Support from DOE ARM to strengthen obs/model collaborations

Model participants expected from at least
11 different universities/research centers

Observational participants expected from at least
6 different universities/research centers

Two main model configurations:
(1) Simplified aerosol (fixed N_d / N_i)
(2) Prog. aerosol (based on upwind measurements)



Diverse set of observational measurements from:
ARM, Ny-Ålesund/Zeppelin Observatory, CALIPSO, Sentinel (SAR), MODIS, and VIIRS

Join us in Breakout Session 6 (Wednesday from 4:15-6:15 PM ET) to learn more, provide feedback, and get involved!

https://comble-intercomparison.readthedocs.io

Summary

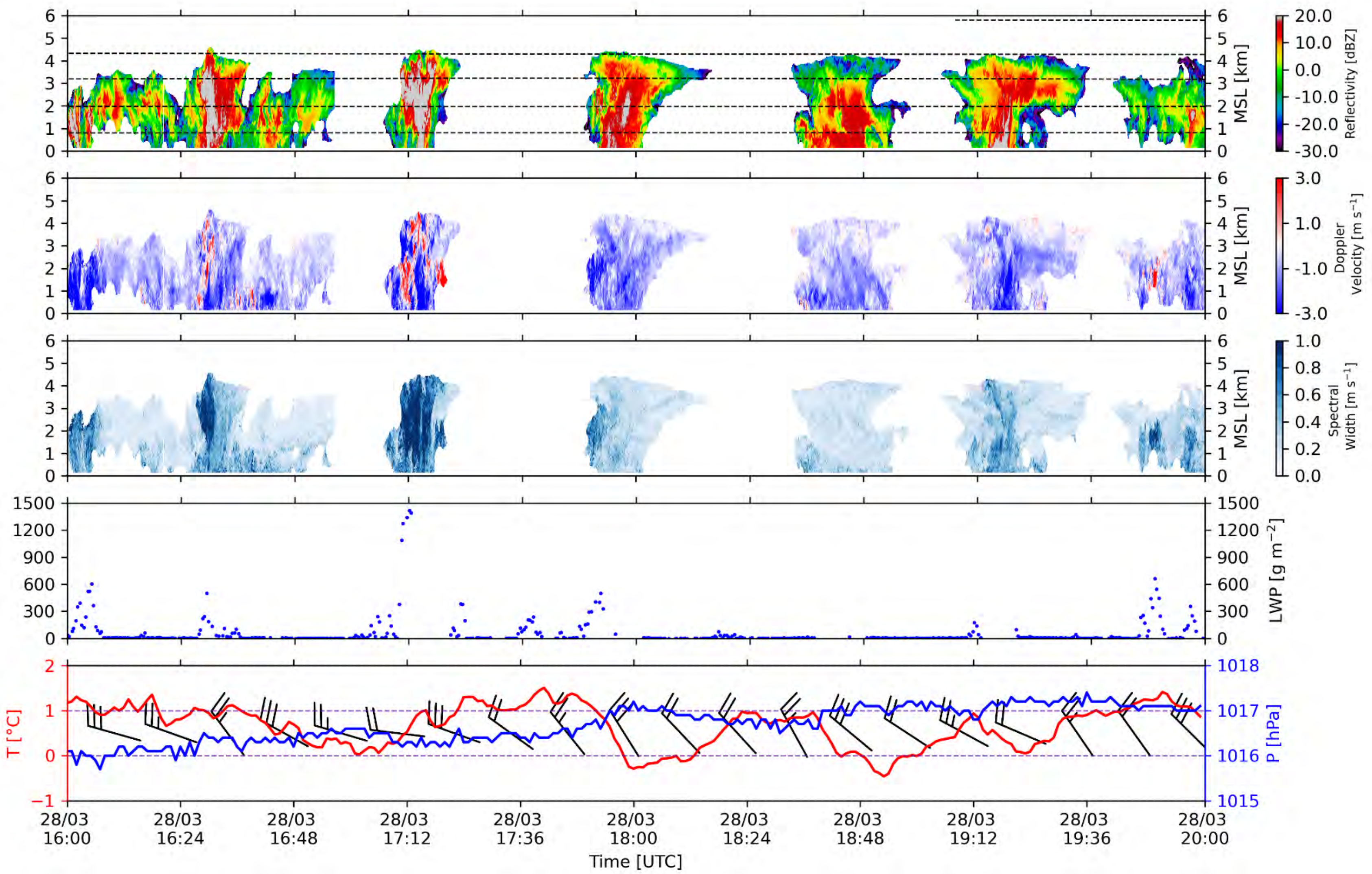
- COMBLE observations and satellite data are combined to describe cloud morphological evolution and vertical structure of the CAO cloud regime.
- Focus of analyses is on two intense CAOs, mainly 13 March 2020.
- Much progress with SCM and LES modeling of fetch-dependent cloud evolution.
- International LES model intercomparison effort in progress.

extra slides

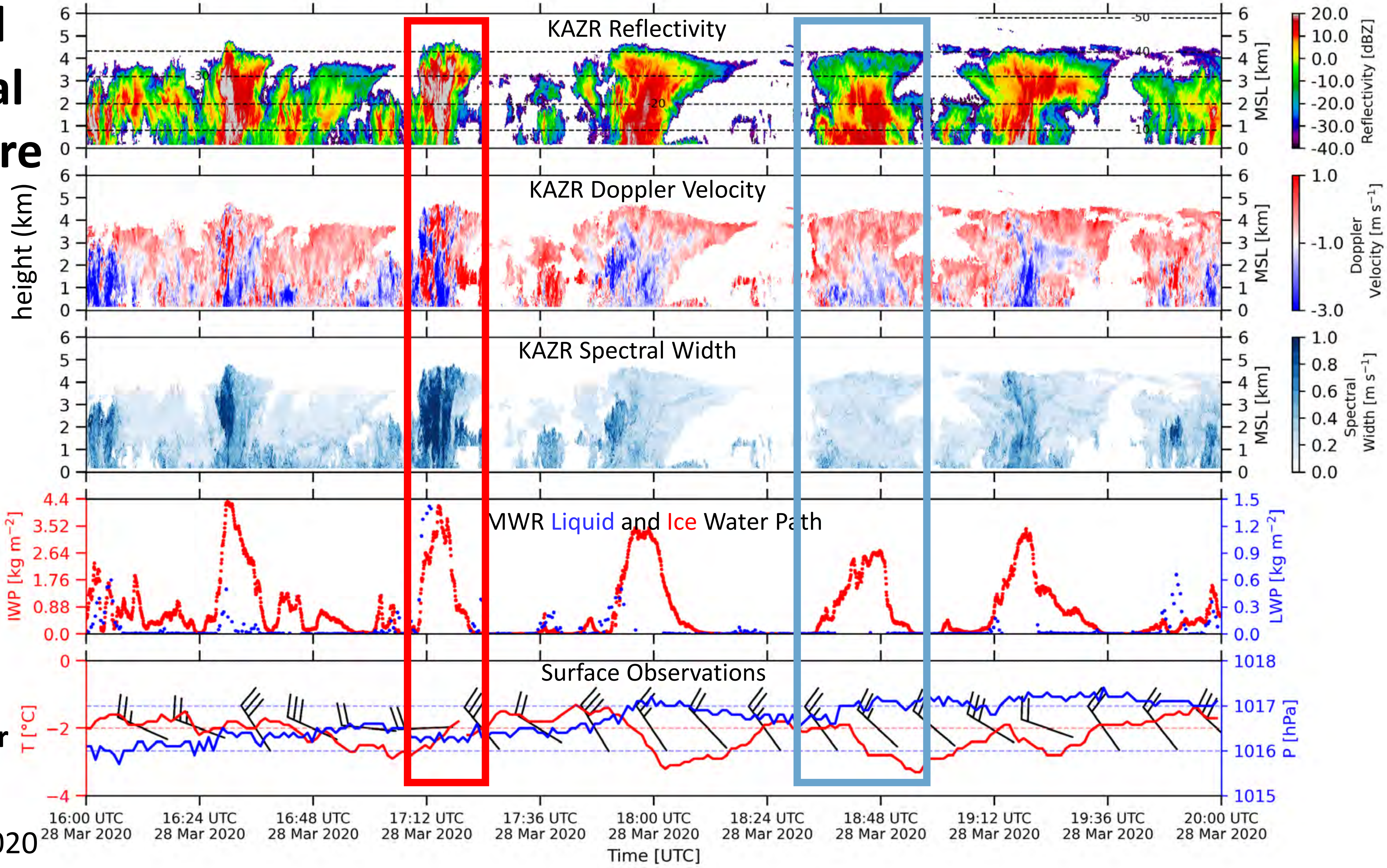
Cellular cloud identification algorithm

Vertical transect with cloud identification algorithm applied

- Smoothing of reflectivity field with a Gaussian filter
- Pixels < - 30 dBZ not counted as part of cloud
- Shallow, small, and elevated cloud structures are removed
- Contiguous cloud structures with multiple strong reflectivity cores are identified as multiple clouds



Cloud vertical structure



open-cellular convection at Andenes March 28, 2020

Cloud street spacing and aspect ratio inferred from satellite imagery

- Suomi NPP/NOAA-20 VIIRS I5 (10.5-12.4 μm) band imagery
- Satellite data is interpolated on a regular grid
- Spectral Analysis along a line perpendicular to BL wind
- The **vertical aspect ratio (AR)** is defined as *width:depth.* It is derived from most significant spectral peak and satellite-retrieved cloud top height
- Technique can similarly be applied to various fields in model data allowing for validation and comparison to observation