


Eastern North Atlantic (ENA) Site Science & Infrastructure

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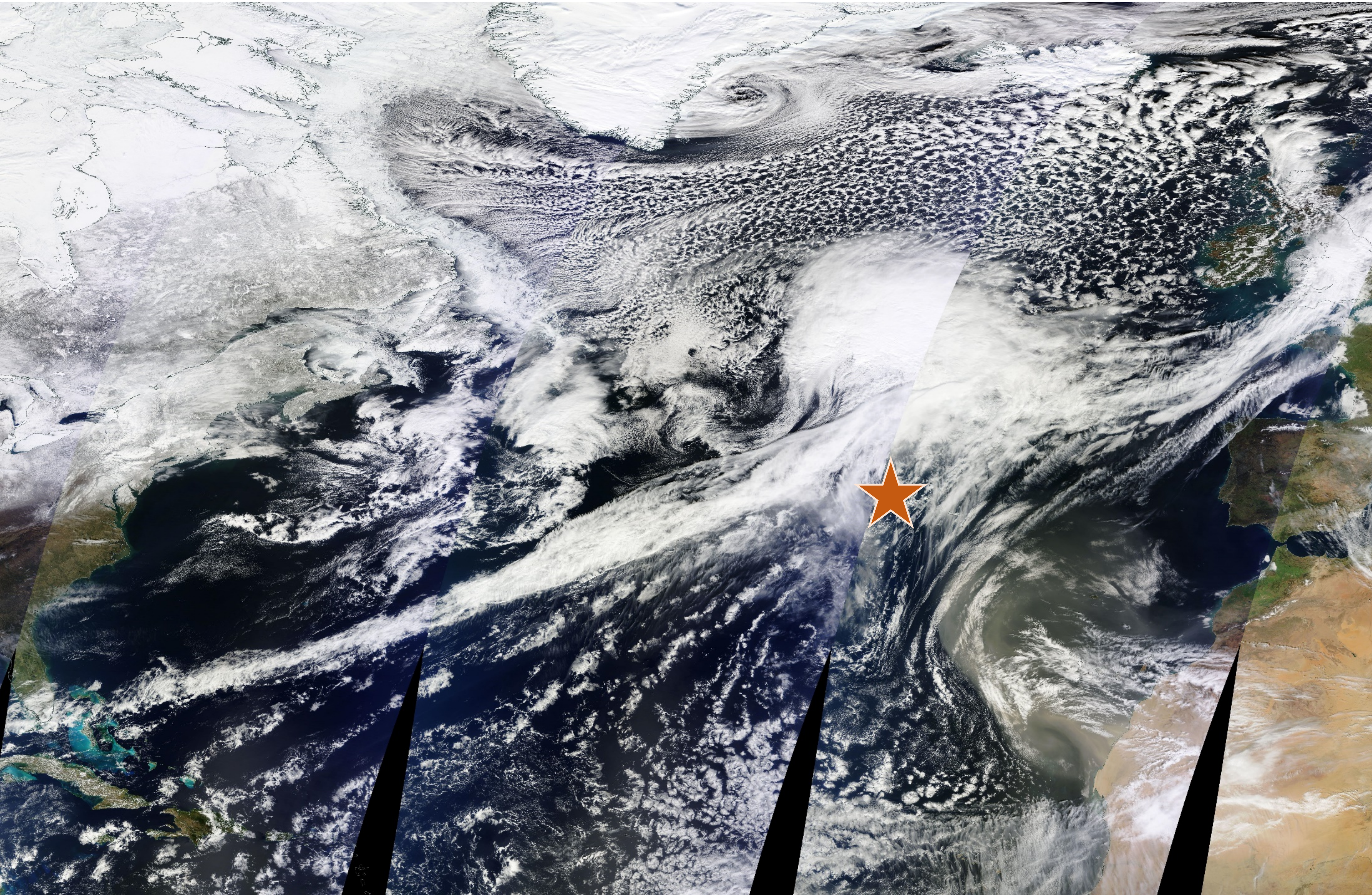
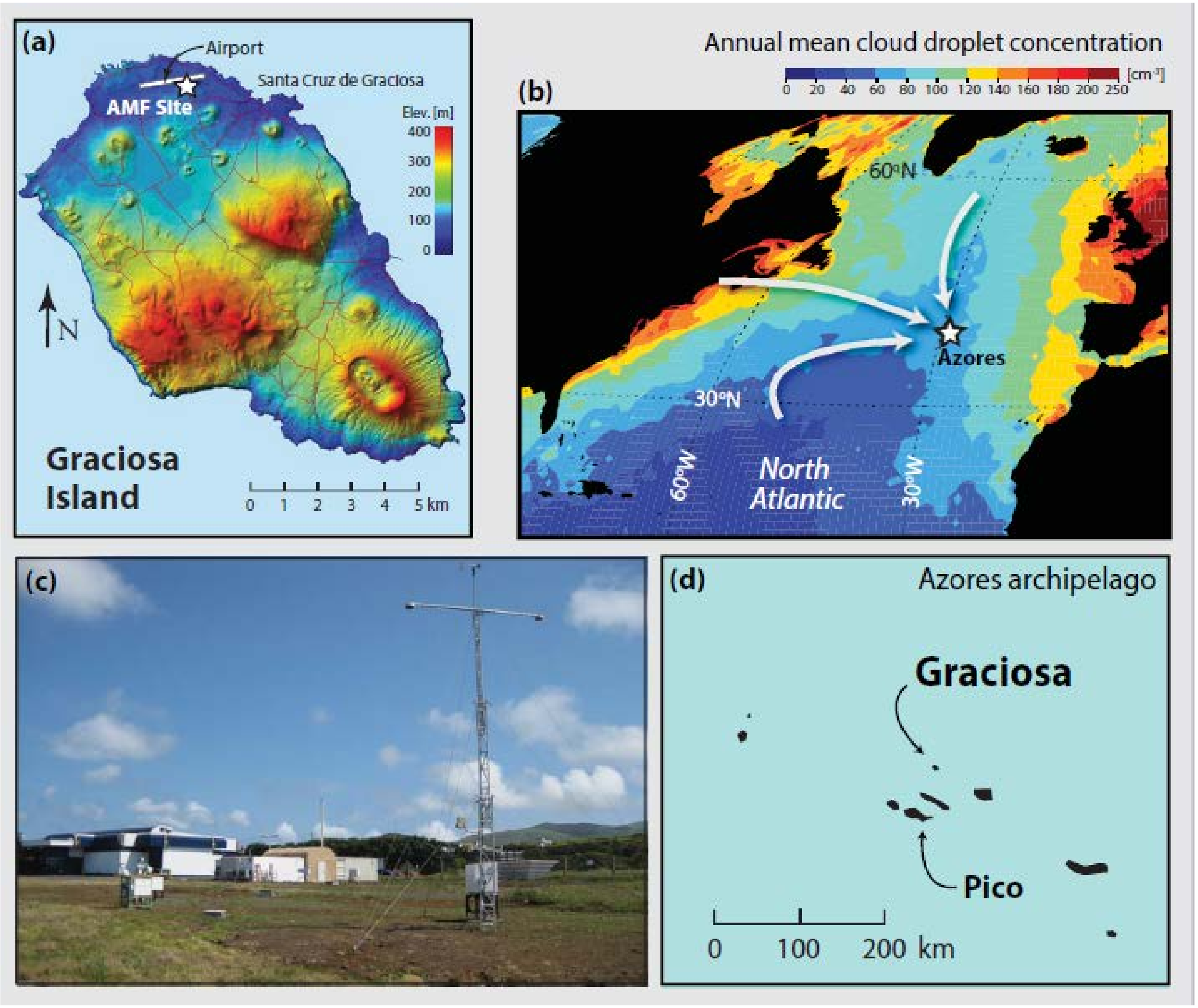
Confluence of Air Masses

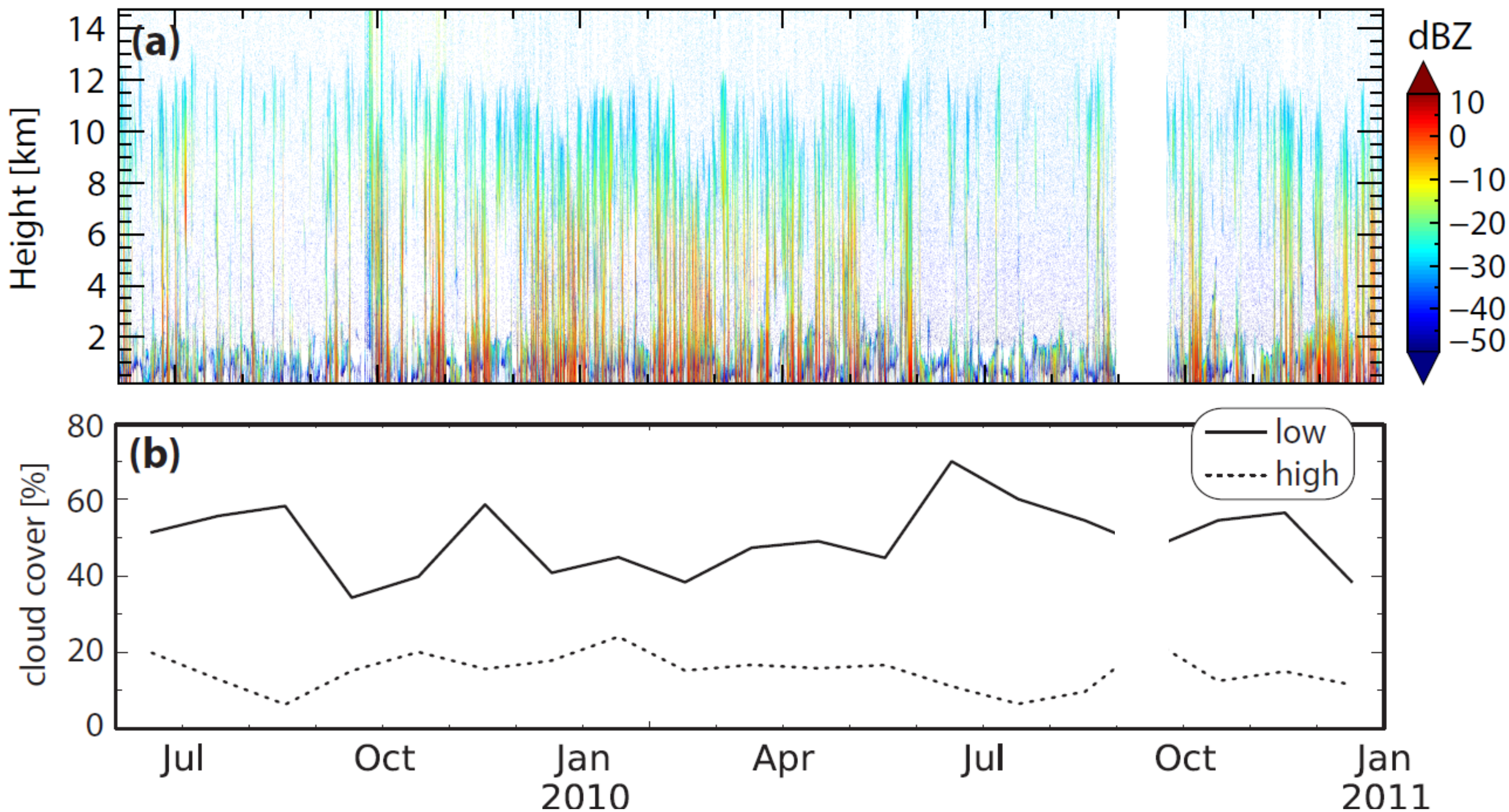


Graciosa

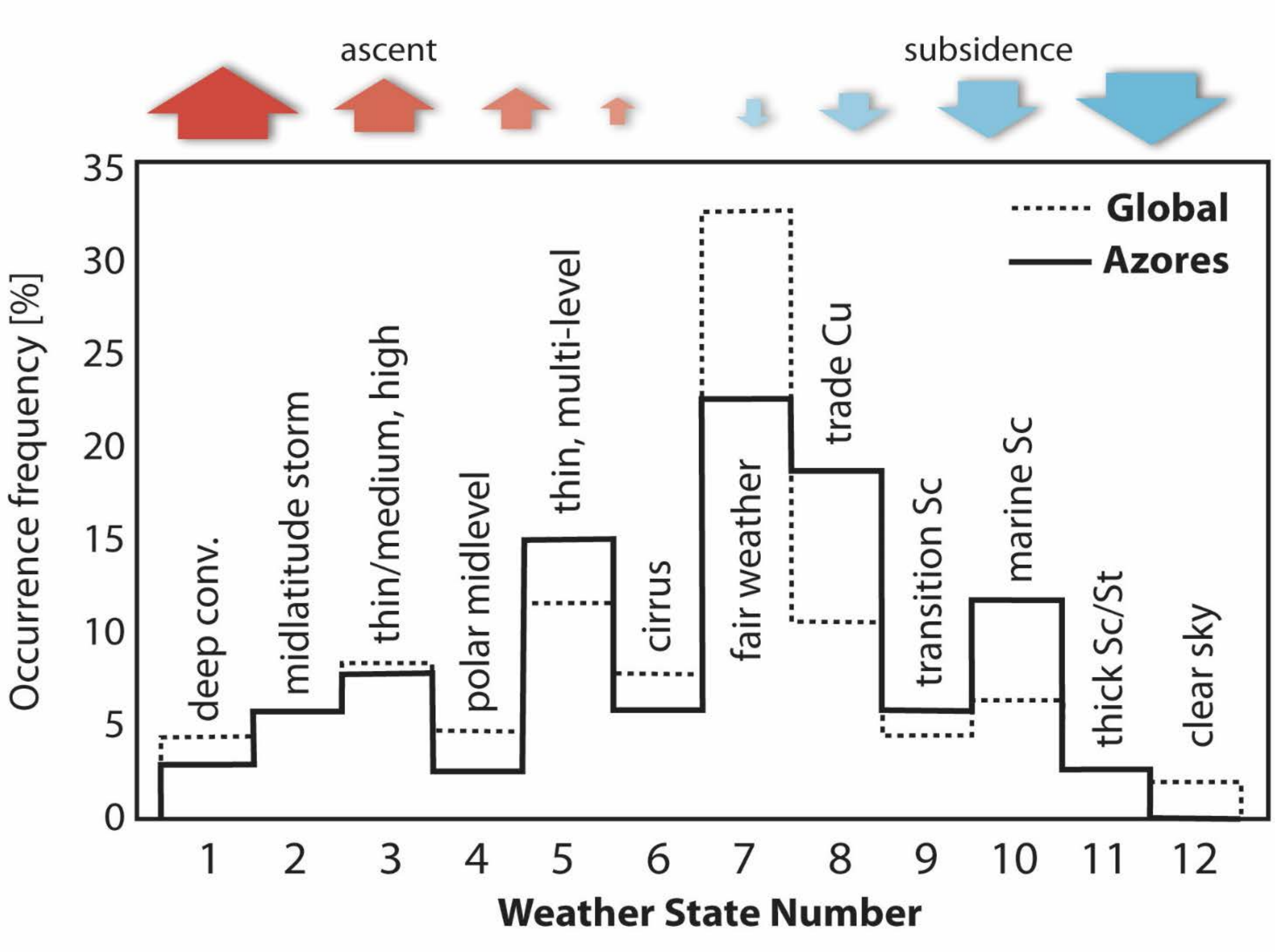
- Situated in the Azores archipelago in the eastern North Atlantic (39°N, 28°W)
- Straddles boundary between subtropics and extratropics
- Remote marine site, receiving air transported from North America, the Arctic, sometimes Europe
- AMF deployed for 21 months – April 2009 to December 2010
- ENA measurements began late 2013



Radar - all 21 months



Distribution of ENA weather states: similar to global values

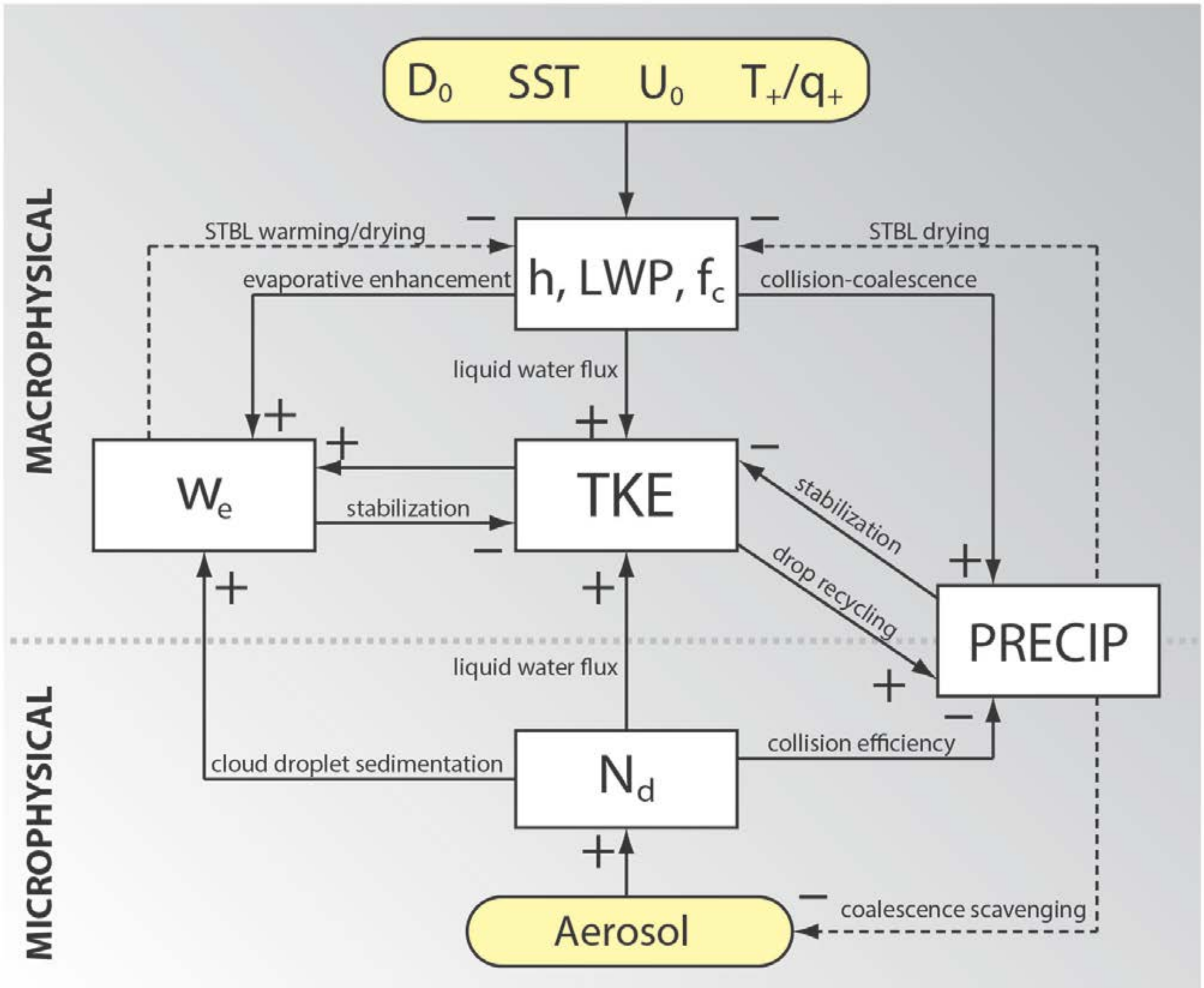


Tselioudis et al. (2013); Rémillard et al. (2015)

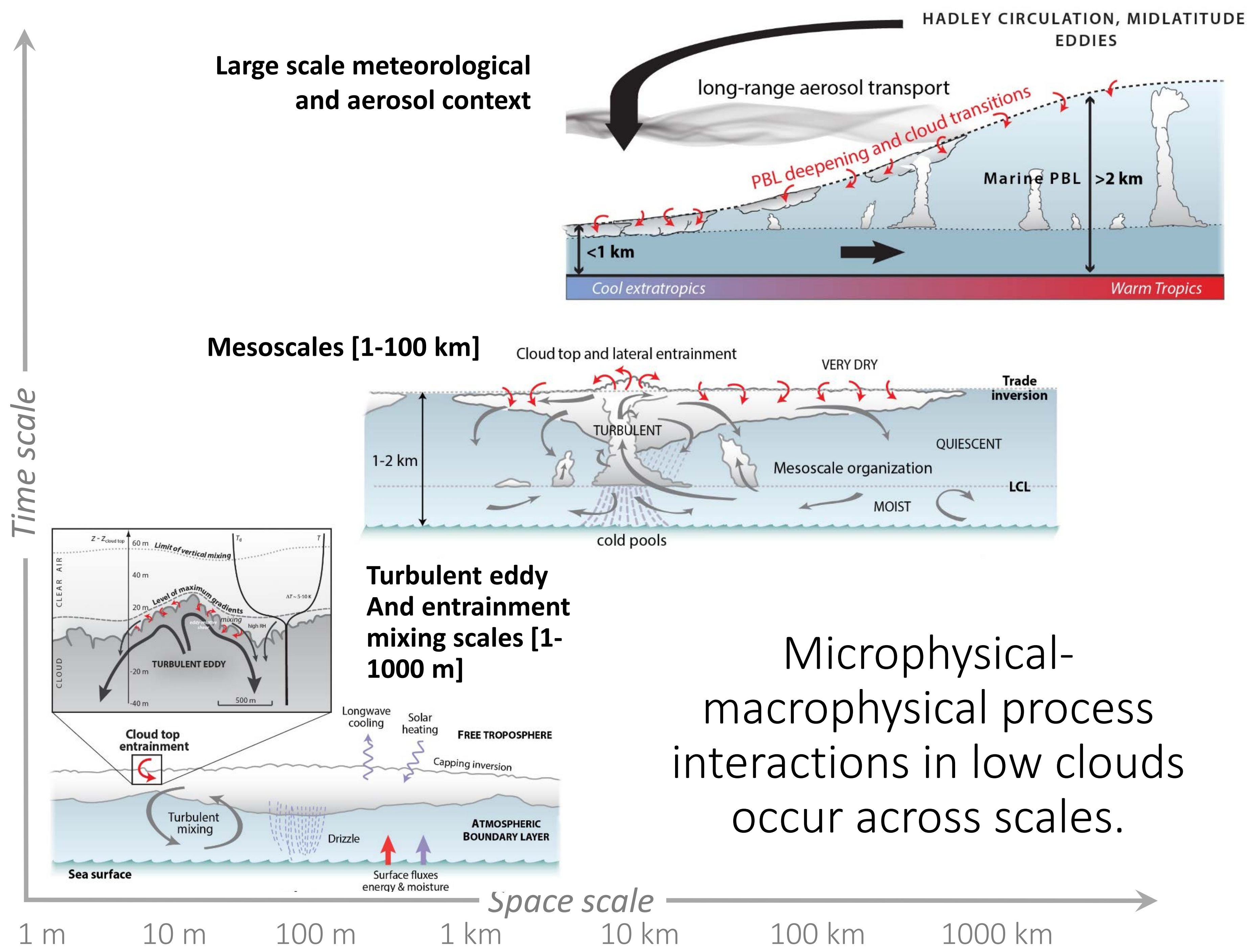
Overarching focus: Microphysical-macrophysical interactions in low cloud systems over the Eastern North Atlantic

- Theme 1. Acquiring process-based understanding of cloud microphysical-macrophysical interactions across scales
- Theme 2. Understanding how microphysical-macrophysical interactions depend upon and influence the aerosol and meteorological environment
- Theme 3. Assessing and improving process and climate model representations of clouds, aerosols and their interactions.

Microphysical-macrophysical interactions: central to low cloud behavior



Adapted from Wood: *Stratocumulus Clouds*, MWR (2012)



Large scale meteorological and aerosol context
HADLEY CIRCULATION, MIDLATITUDE EDDIES
long-range aerosol transport
PBL deepening and cloud transitions
Marine PBL
>2 km
<1 km
Cool extratropics
Warm Tropics
Mesoscales [1-100 km]
Cloud top and lateral entrainment
VERY DRY
Trade inversion
TURBULENT
QUIESCENT
1-2 km
Mesoscale organization
LCL
MOIST
cold pools
Turbulent eddy And entrainment mixing scales [1-1000 m]
Limit of vertical mixing
Level of maximum gradients
TURBULENT EDDY
CLEAR AIR
CLOUD
60 m
40 m
20 m
-20 m
-40 m
500 m
high RH
Cloud top entrainment
Longwave cooling
Solar heating
FREE TROPOSPHERE
Capping inversion
Turbulent mixing
Drizzle
ATMOSPHERIC BOUNDARY LAYER
Sea surface
Surface fluxes energy & moisture
Microphysical-macrophysical process interactions in low clouds occur across scales.
Time scale
Space scale
1 m
10 m
100 m
1 km
10 km
100 km
1000 km

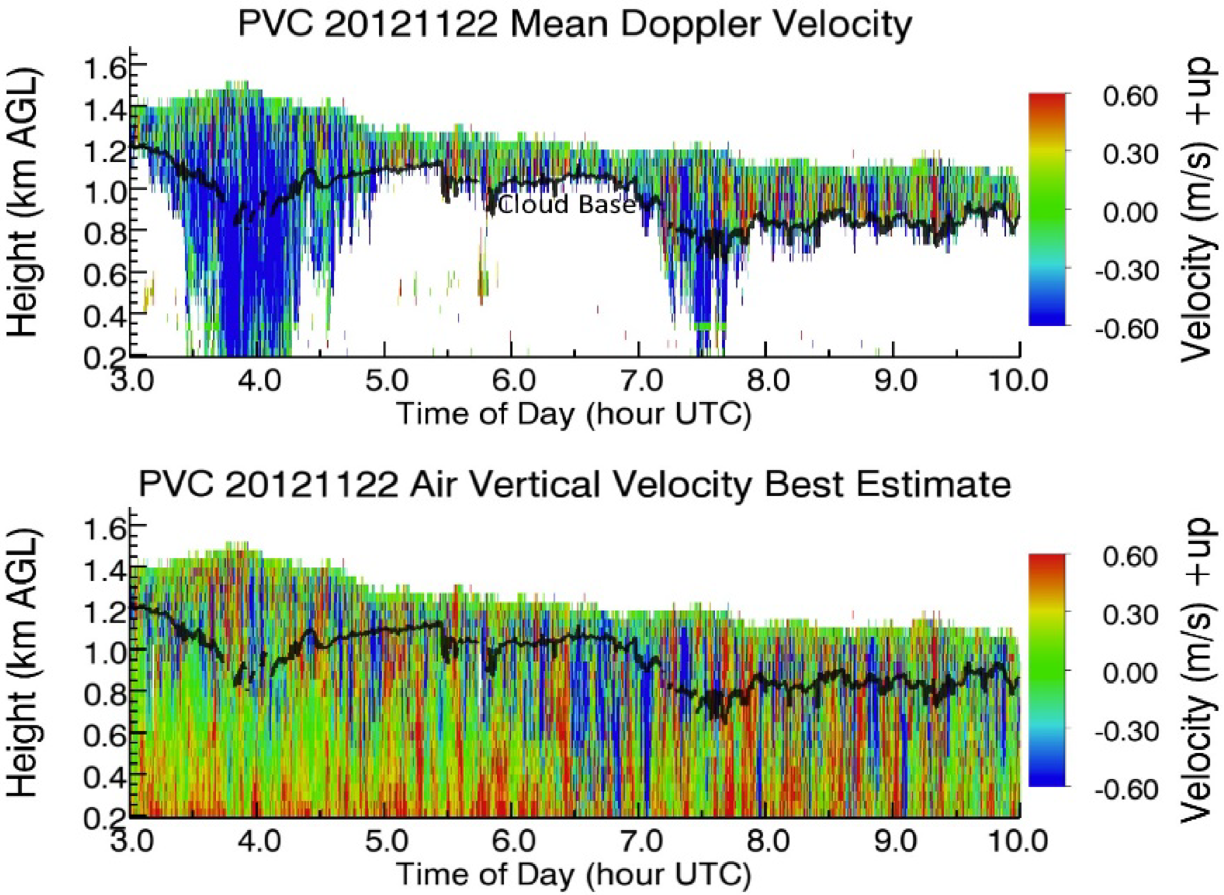
Remote sensing instrumentation

Instrument(s)		Key derived parameters
RADARS	Ka-band ARM Zenith Radar (KAZR)	(i) Cloud and precipitation vertical structure (iii) Drizzle drop size distribution using both Doppler spectral measurements and with lidar (O'Connor et al. 2005)
	Ka-band and W-band Scanning ARM Cloud Radar (KaW-SACR)	(i) 3D cloud and drizzle structure up to 20 km range (ii) Dual-wavelength observations (retrieval of LWC) (iii) 3D cloud dynamics and turbulence
	X-band Scanning ARM Precipitation Radar (X-SAPR2)	(i) Areal precipitation rate and hydrometeor type (ii) Doppler winds in precipitating systems
	Radar Wind Profiler (RWP)	(i) Horizontal wind profiles and virtual temperature profiles (ii) Unattenuated profiling radar moments of drizzle/precipitation (iii) Inversion height and strength
LIDARS	Ceilometer (VCEIL) and Micropulse Lidar (MPL)	(i) Cloud base height and cloud cover (ii) Precipitation profiling below cloud base (with radar)
	Raman Lidar (RL)	(i) Aerosol extinction profile (ii) Water vapor profe
	Doppler Lidar (DL)	(i) Vertical turbulent wind component (ii) Horizontal wind fields
MWR	Microwave Radiometer (MWR) – 23/31/90 GHz	Column liquid water and water vapor path
	Microwave Profiler	(i) Temperature and mixing ratio profiles
VISIBLE AND IR RADIOMETERS	MultiFilter Rotating Shadowband Radiometer (MFRSR); Sunphotometer	(i) Cloud visible optical thickness. Cloud microphysical properties (droplet concentration, effective radius) in combination with MWR (ii) Aerosol optical properties in clear skies
	Atmospheric Emitted Radiance Interferometer ("ASSIST")	Cloud liquid water path (LWP) estimates for thin clouds (combined with MWR, following Turner 2007)
	Broadband and Spectral Radiometers	SW and LW radiative fluxes used to constrain the surface energy budget; spectrally resolved radiances for microphysical and LWC retrievals
	Total Sky Imager (TSI)	Cloud coverage and type

In situ instrumentation

Instrument	Key derived parameters
Balloon-borne Sounding System (BBSS)	(i) Atmospheric profile of temperature, humidity and winds (ii) MBL depth (iii) Inversion strength
Eddy Correlation Systems (ECOR)	Surface turbulent fluxes of latent and sensible heat
Surface Meteorological Instruments	Surface temperature, humidity, pressure, winds, precipitation rate (optical and tipping bucket rain gauges, disdrometer)
Surface aerosol observing system	Total aerosol concentration > 10 nm diameter (CN counter);
	CCN spectra at seven supersaturations (nominally 0.1, 0.2, 0.3,0.5, 0.8, 1, 1.1%)
	Aerosol size distribution from 60-1000 nm (UHSAS)
	Dry (low RH) and wet (scanning RH from 40-90%) aerosol scattering (total and hemispheric backscattering) at three wavelengths (450, 550 and 700 nm) with 1 and 10 micron size cut-off;
	Aerosol absorption (PSAP) at three wavelengths (450, 550 and 700 nm) wavelength
	Hygroscopic aerosol size growth (TDMA)
	Aerosol chemical speciation (Aerosol Mass Spectrometer)
Gas tracers	Carbon monoxide/dioxide, nitrous oxide, methane

TASK 1.1	Development of retrievals of vertical air motion and cloud and drizzle microphysics for application to marine low clouds

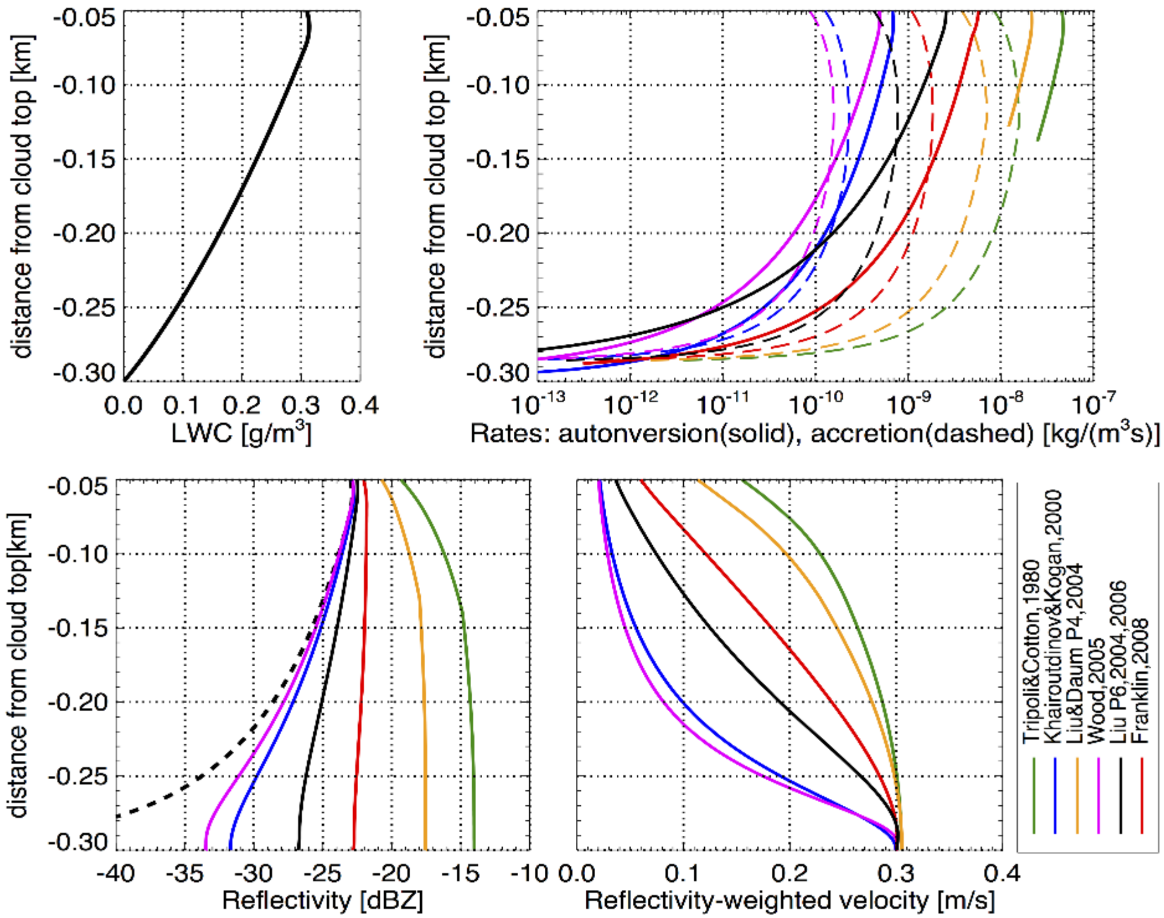


Mean Doppler velocity from the 94-GHz radar at TCAP during a stratocumulus case. Periods with and without drizzle are observed (top). Vertical air motion from the ground to the cloud top using the radar and lidar Doppler retrievals (bottom).

TASK 1.2	Application of new retrievals to characterizing relationships between microphysical and macrophysical structures and processes
SUBTASK 1.2a	Investigate the representation of particle growth processes in numerical models using forward and inverse modeling of radar Doppler spectra observations and 1-D steady-state process bin models.

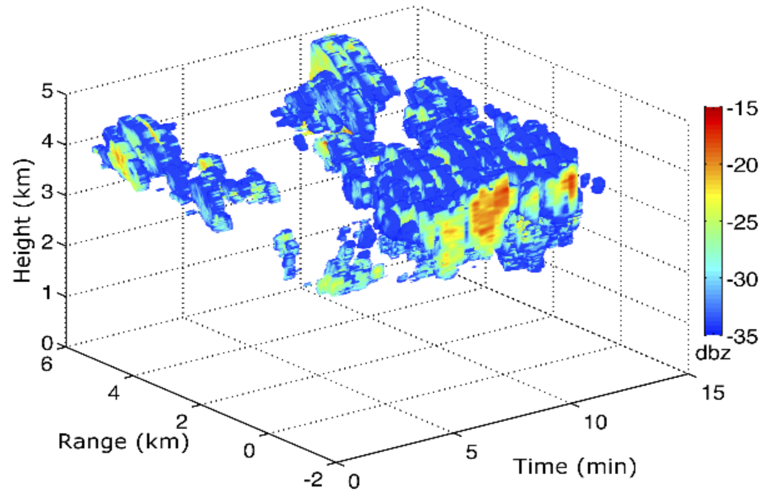
Testing microphysical process rate formulations using retrievals.

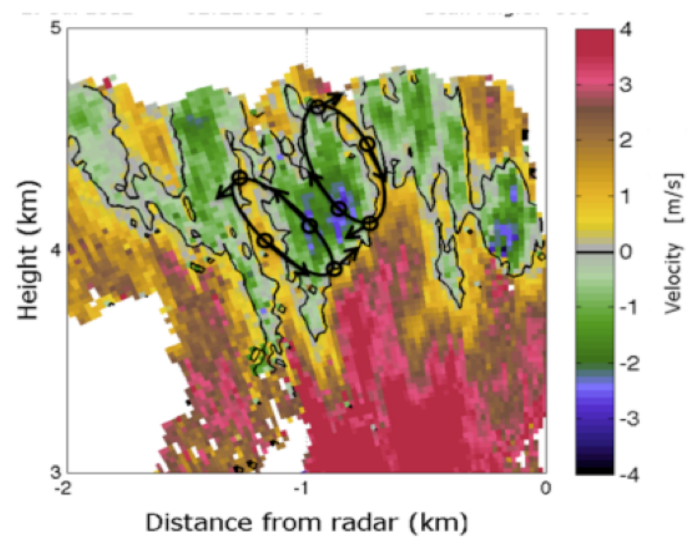
Cloud LWC retrievals from CAP-MBL observations (top left) are used to estimate the formation rate of embryonic drizzle droplets due to autoconversion (top right, colors represent different formulations). The accretion process is explicitly modeled (top right). The cloud and drizzle microphysical model is used as input to a radar Doppler spectrum forward model and synthetic spectral moments are generated (bottom). Both the radar reflectivity profiles (bottom left, black dotted line is the cloud-only radar reflectivity profile) and the mean Doppler velocity profiles (bottom right) exhibit great sensitivity to the autoconversion formulation.



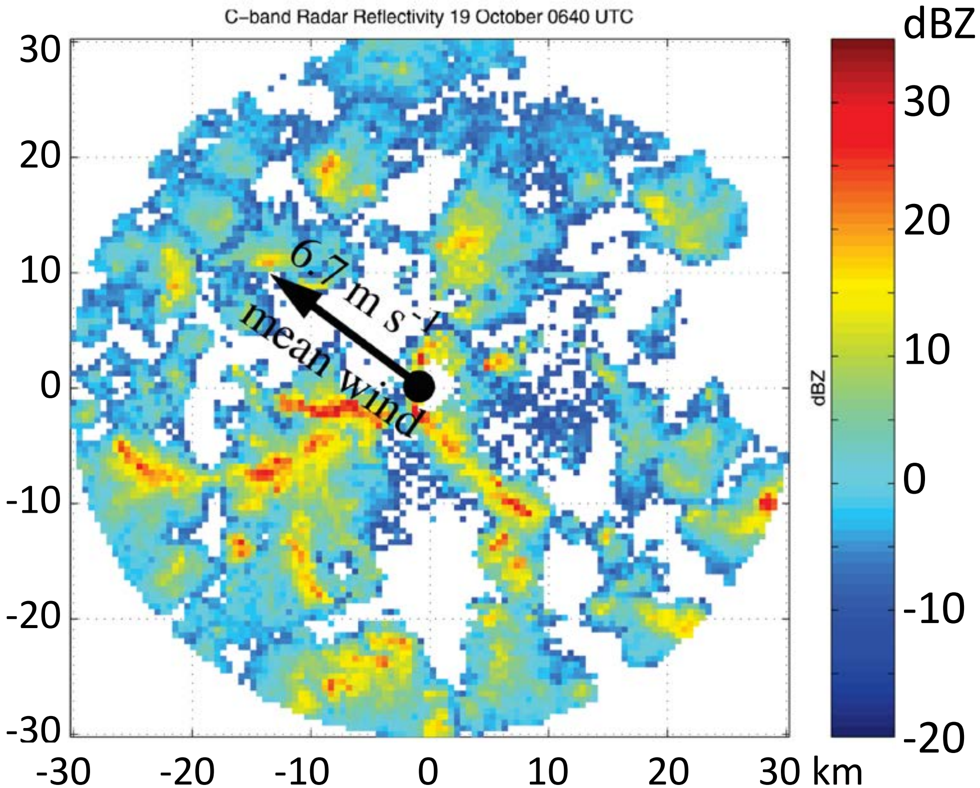
TASK 1.2	Application of new retrievals to characterizing relationships between microphysical and macrophysical structures and processes
SUBTASK 1.2b	Investigate how entrainment acts (cloud top or lateral boundaries, physical scales) in shallow cumulus clouds and its impact on microphysics using comprehensive ARM observations from profiling and scanning sensors

Example of gridded 3D Ka-SACR reflectivity observations from a shallow cumuli field (top) and a 2-D slice of Doppler Velocity observations (bottom) from one of the Cross-Wind RHI scans during the Two-Column Aerosol Project (TCAP). The schematic of the toroidal circulation is plotted with black arrows

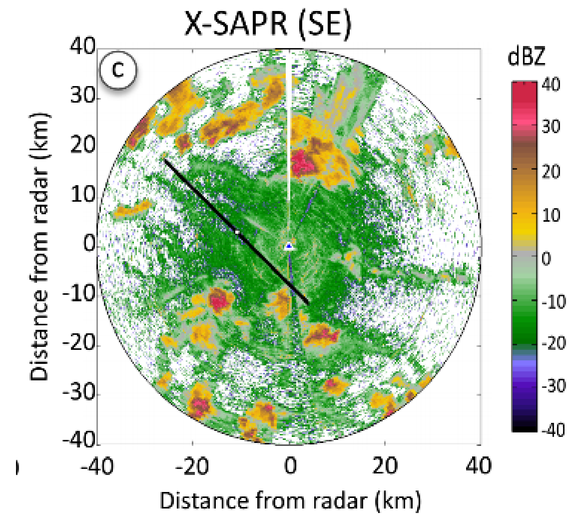


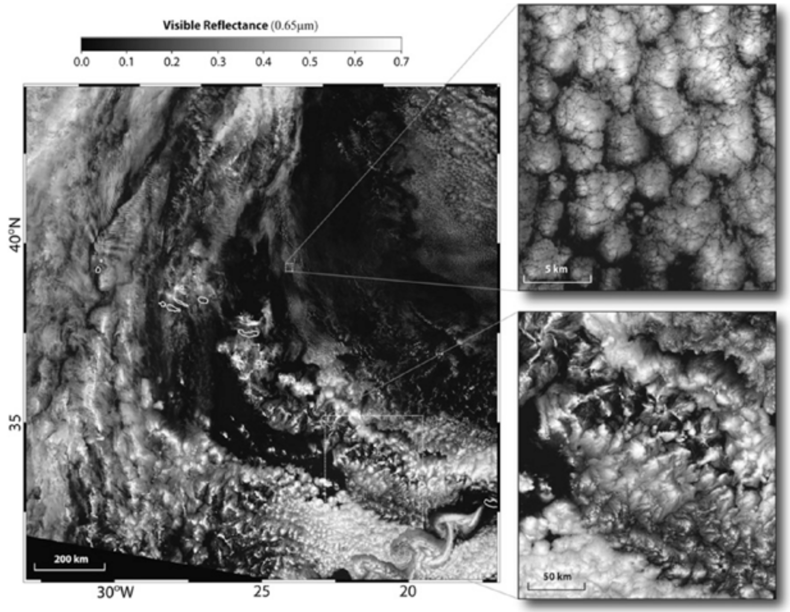


TASK 1.2	Application of new retrievals to characterizing relationships between microphysical and macrophysical structures and processes
SUBTASK 1.2c	Characterize and understand the organizational structure and dynamics of mesoscale cellular convection in marine boundary layer (MBL) clouds;



C-band of mesoscale cells from SE Pacific
Bretherton et al. (2004)





Satellite images of the Azores region show a great wealth of mesoscale organization in low clouds

Mesoscale cellular convection: sampling strategy

Instrument combinations to generate observational turbulent flux estimates.

Flux Profile	w'	Variable	Instruments
Thermal	Doppler Lidar KAZR RWP	θ'	MWRP AERI
Water Vapor	Doppler Lidar KAZR RWP	q'	Raman Lidar MWRP AERI
Condensed Water	KAZR SACR MWR	q'_{liquid}	SACR MWR AERI
Momentum	Doppler Lidar KAZR RWP	u', v'	Doppler Lidar SACR X-Band

RADARS

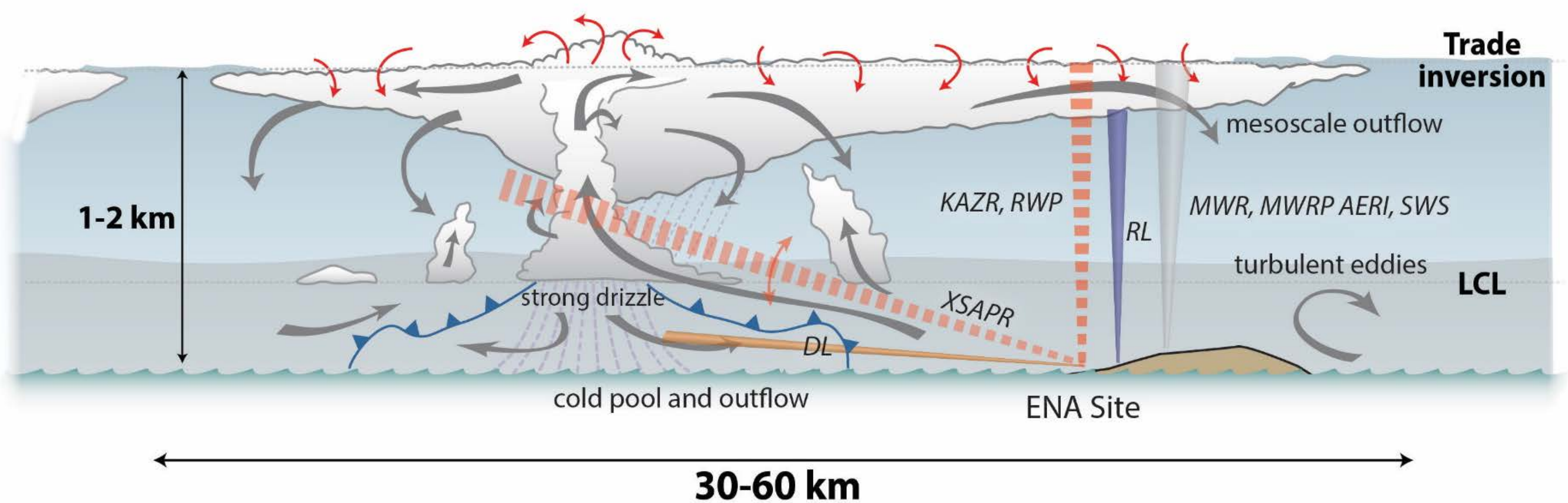
KAZR (Cloud radar)	*Cloud and drizzle reflectivity profile, Doppler spectra*
SACR (Scanning cloud radar)	*Cloud horizontal and vertical structure and in-cloud Doppler winds*
XSAPR (X-band precip. radar)	*Precipitation features and associated horizontal winds*
RWP (Radar wind profiler)	*Horizonal virtual temperature and wind profiles*

LIDARS

DL (Doppler Lidar)	*Horizontal and vertical mesoscale wind features using Doppler, turbulence*
RL (Raman Lidar)	*Aerosol and water vapor profiles in MBL*

PASSIVE INSTRUMENTS

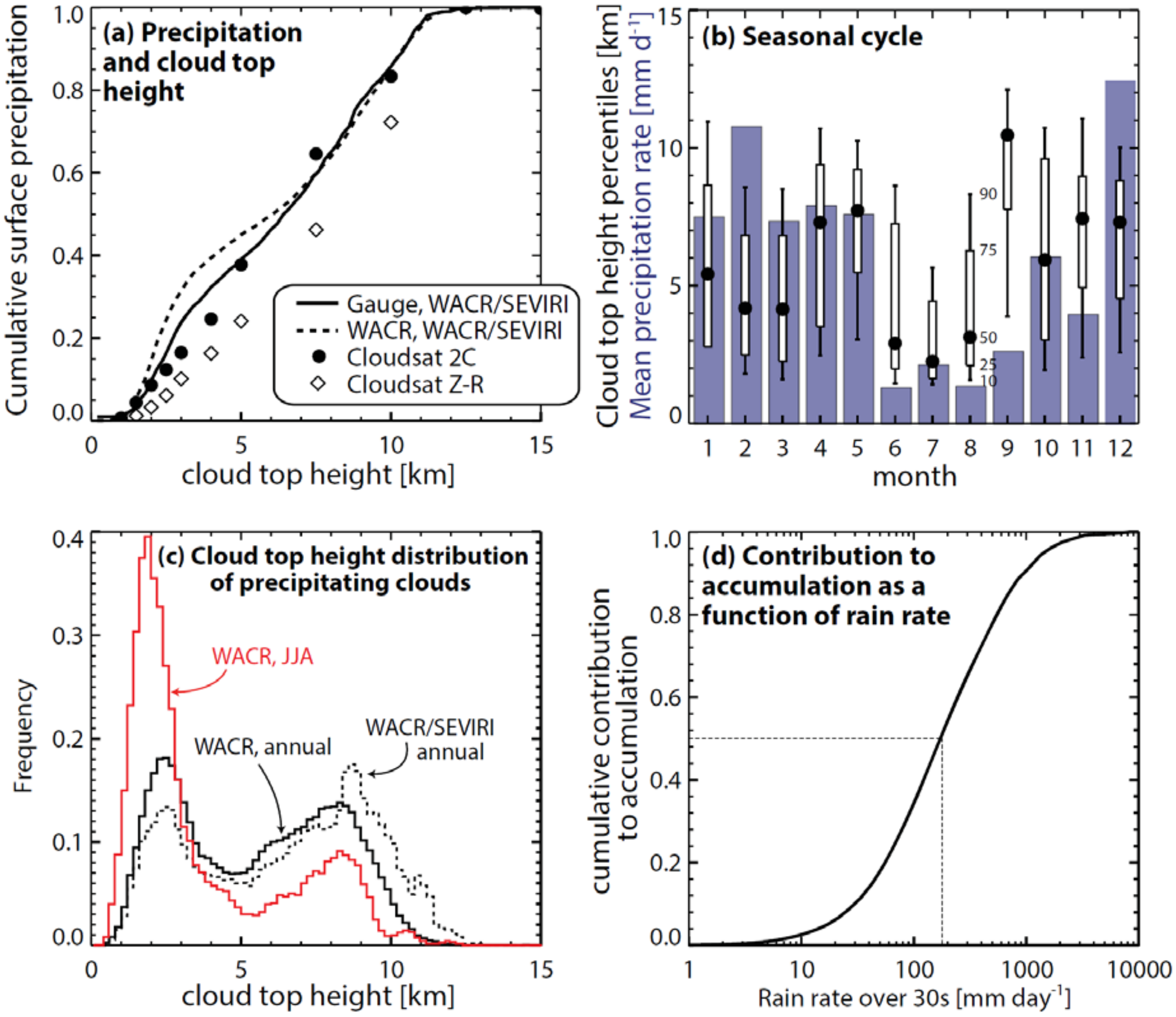
MWR (Microwave radiometer)	*Liquid water path*
AERI (IR spectral radiometer)	*Liquid water path in thin clouds. Water vapor profiles*
SWS (Shortwave spectrometer)	*Cloud optical thickness, effective radius/droplet concentration*



Precipitation:

TASK 2.1	Quantification of precipitation rate and microphysical process rates as a function of cloud type, heights and mesoscale structures;

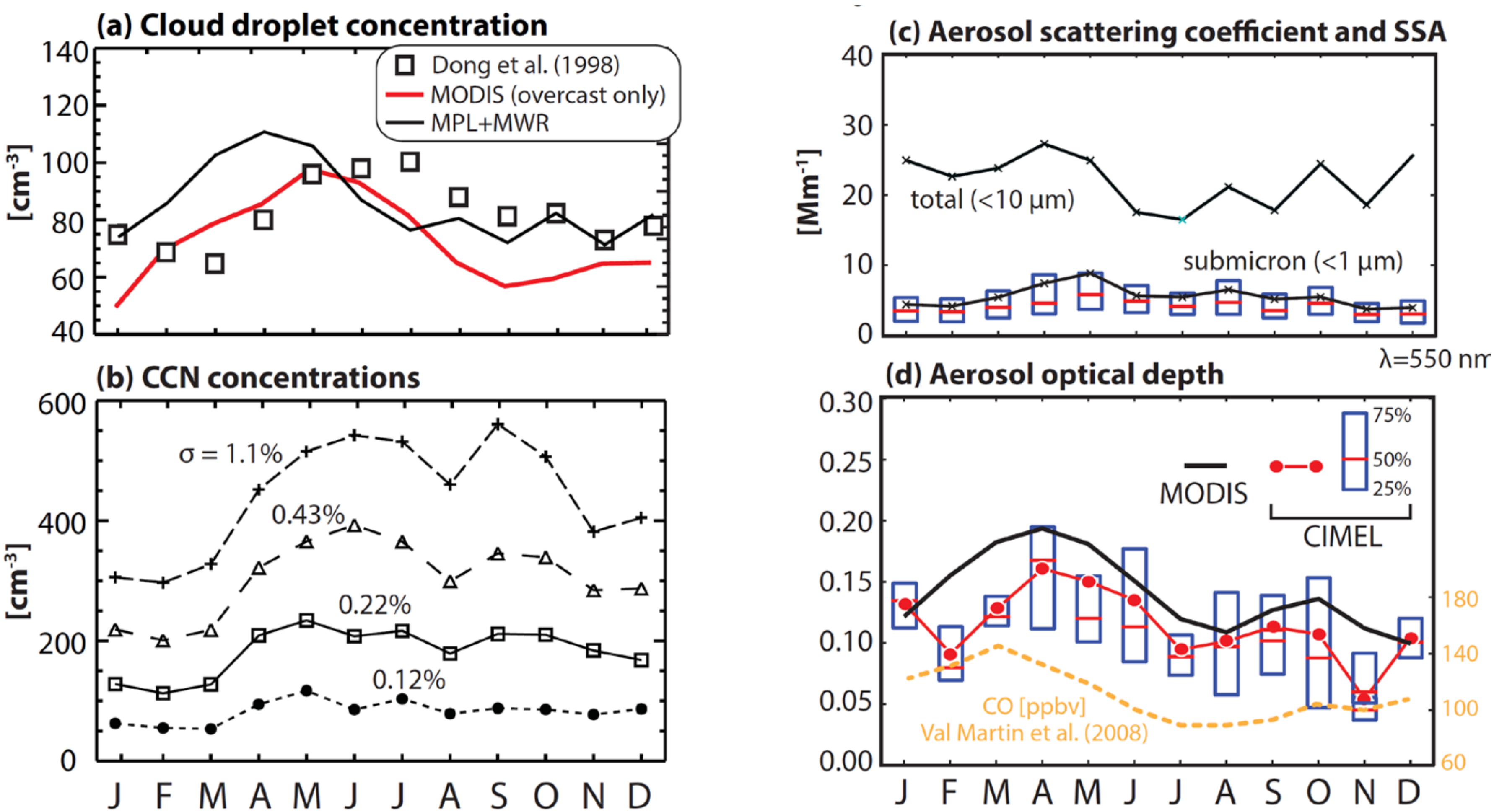
- Clouds with a wide range of top heights (CTH) contribute to surface precipitation at Graciosa
- Precipitation dominated by low clouds during summer
- Approximately half of all clouds are precipitating (Rémillard et al. 2012)



Wood et al. (2015, BAMS)

What drives variability in cloud microphysical and aerosol properties?

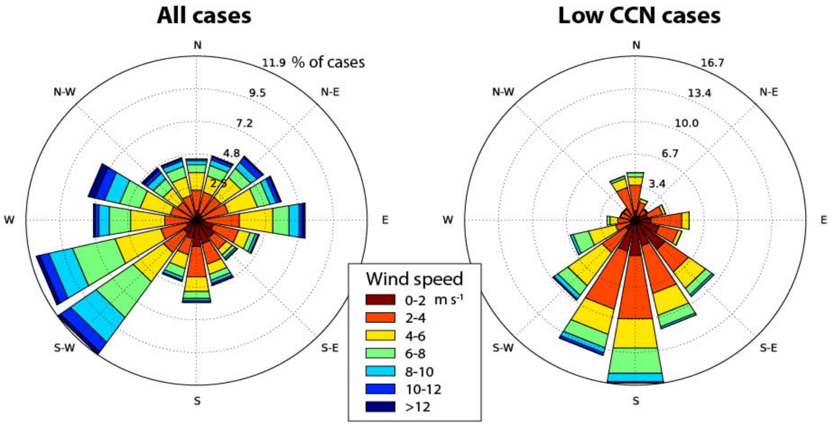
TASK 2.2	Characterization of cloud condensation nucleus concentration (CCN) variability as a function of the large scale, seasonally varying flow using a suite of compositing and trajectory approaches.



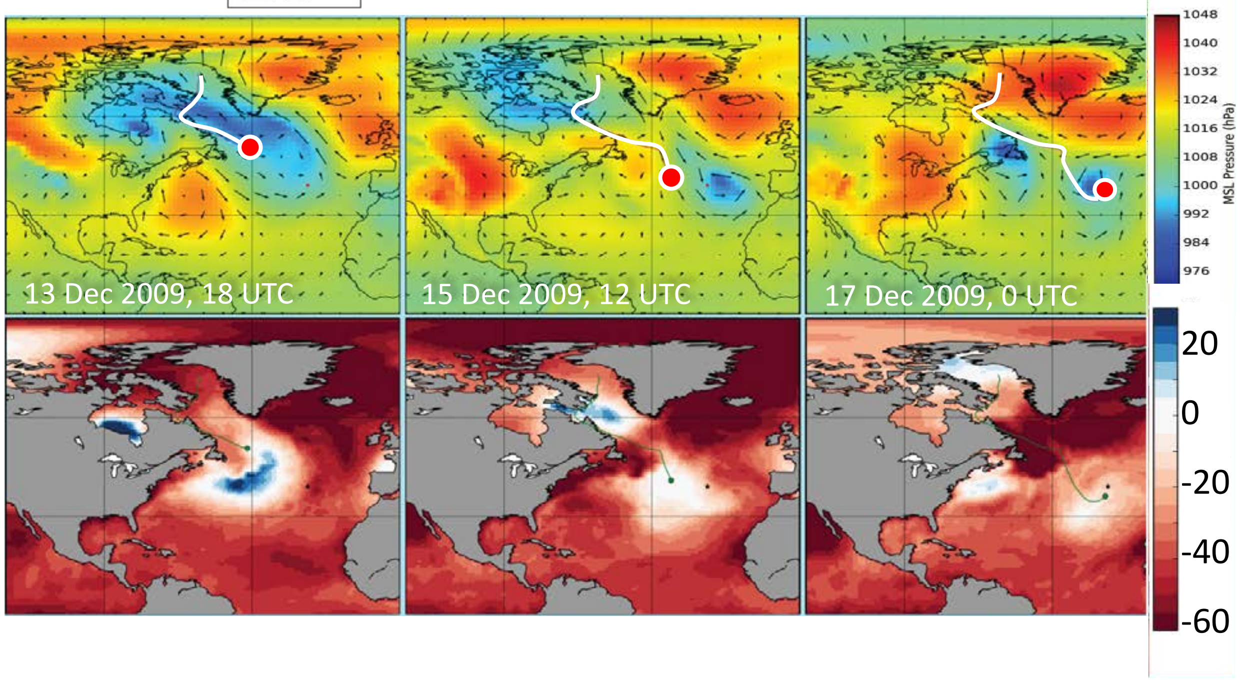
Wood et al. (2015, BAMS)

Coalescence scavenging

TASK 2.3	Quantification of how microphysical-macrophysical interactions work to remove aerosol through wet deposition/coalescence scavenging;



- Low CCN events at Graciosa occur during particular meteorological conditions with light winds and mostly Southerly flow
- Trajectories reveal that many low CCN events occur when cold air outbreaks reach Graciosa



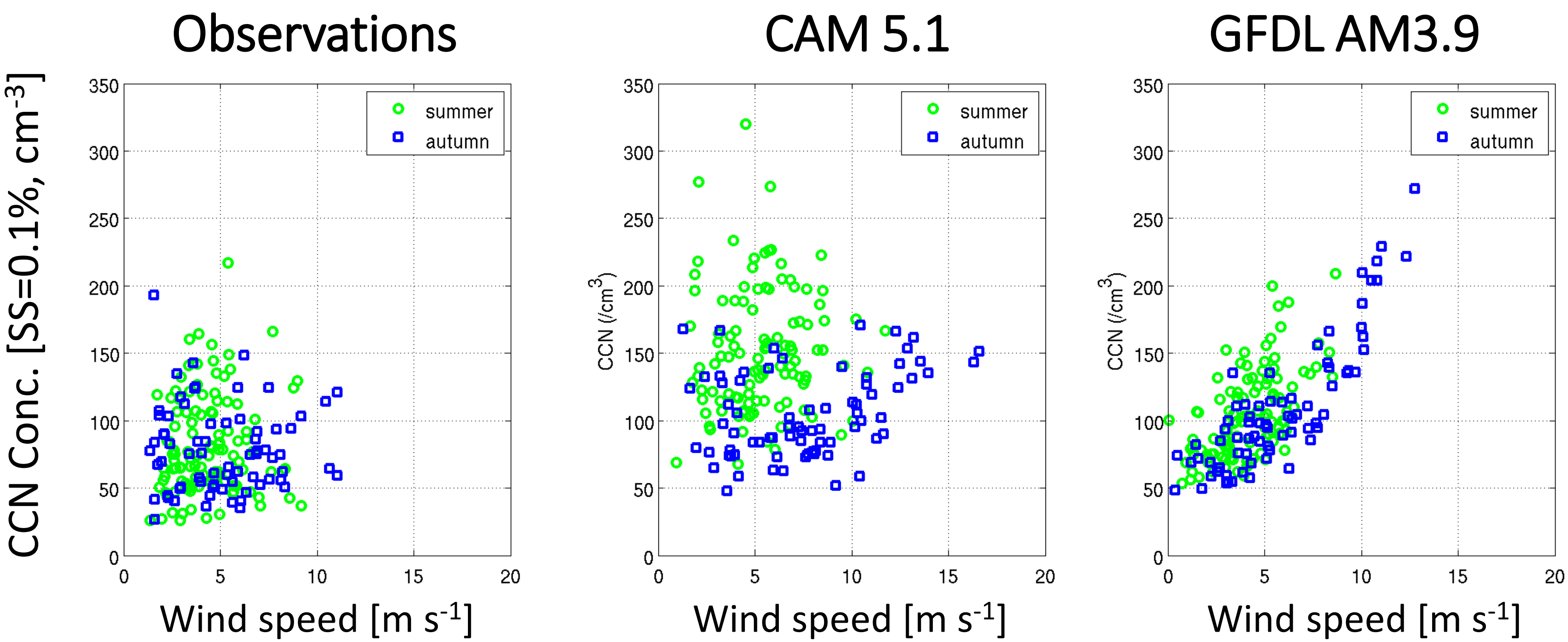
Sea level pressure [hPa]

Cold air outbreak index (Kolstad) [K]

Stemmler et al. (2015)

TASK 3.1	Evaluate microphysical-macrophysical relationships implicit in higher order turbulence closure schemes by combining cloud and clear-sky kinematic observations from radars and lidars with cloud microphysical retrievals.
TASK 3.2	Conduct a large scale model assessment project, focusing on both clouds and aerosols that will focus the climate modeling community and help drive model improvements by providing key constraints needed to identify model errors;

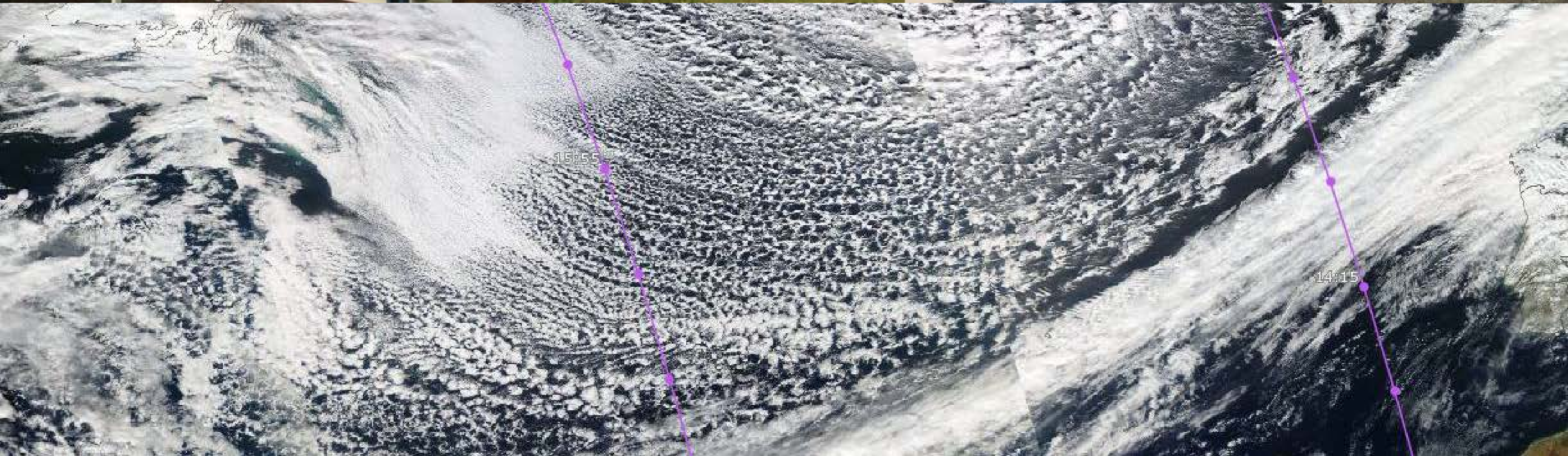
- Observations: weak CCN dependence on wind speed
- CAM 5.1: general agreement; GFDL AM3.9: strong wind speed dependence
- Need to better understand factors controlling CCN budget



Wyant et al. (2015)

New measurement systems in the marine low cloud environment

- Raman Lidar
  - Aerosol extinction profiles
  - Temperature/humidity profiles $\Rightarrow$ RH
  - Improved CCN profile
  - Cloud retrievals for thin clouds
- KaW SACR
  - Dual frequency $\Rightarrow$ differential attenuation $\Rightarrow$ LWC
  - Scanning capability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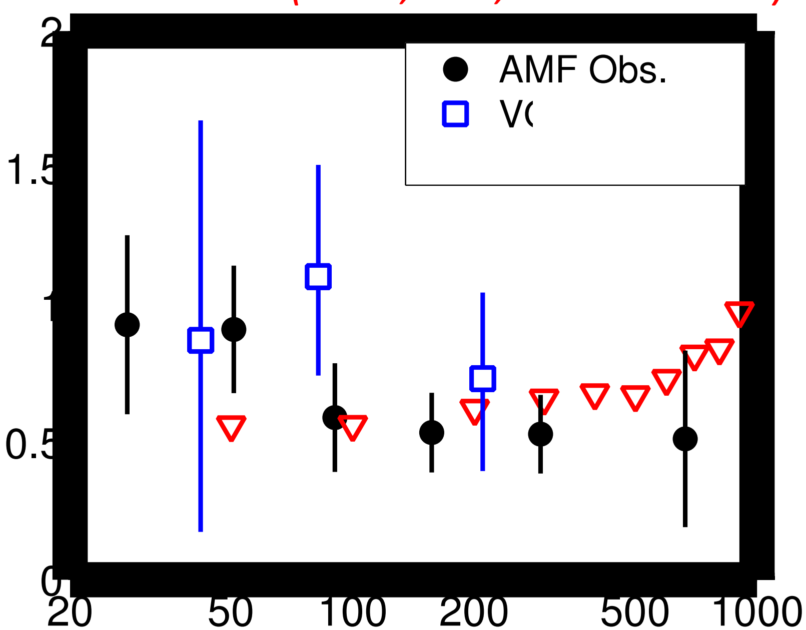
Graciosa
São Jorge
Faial
Terceira
Pico
AZORES
AZORES
São Miguel
ATLANTIC OCEAN
Santa Maria

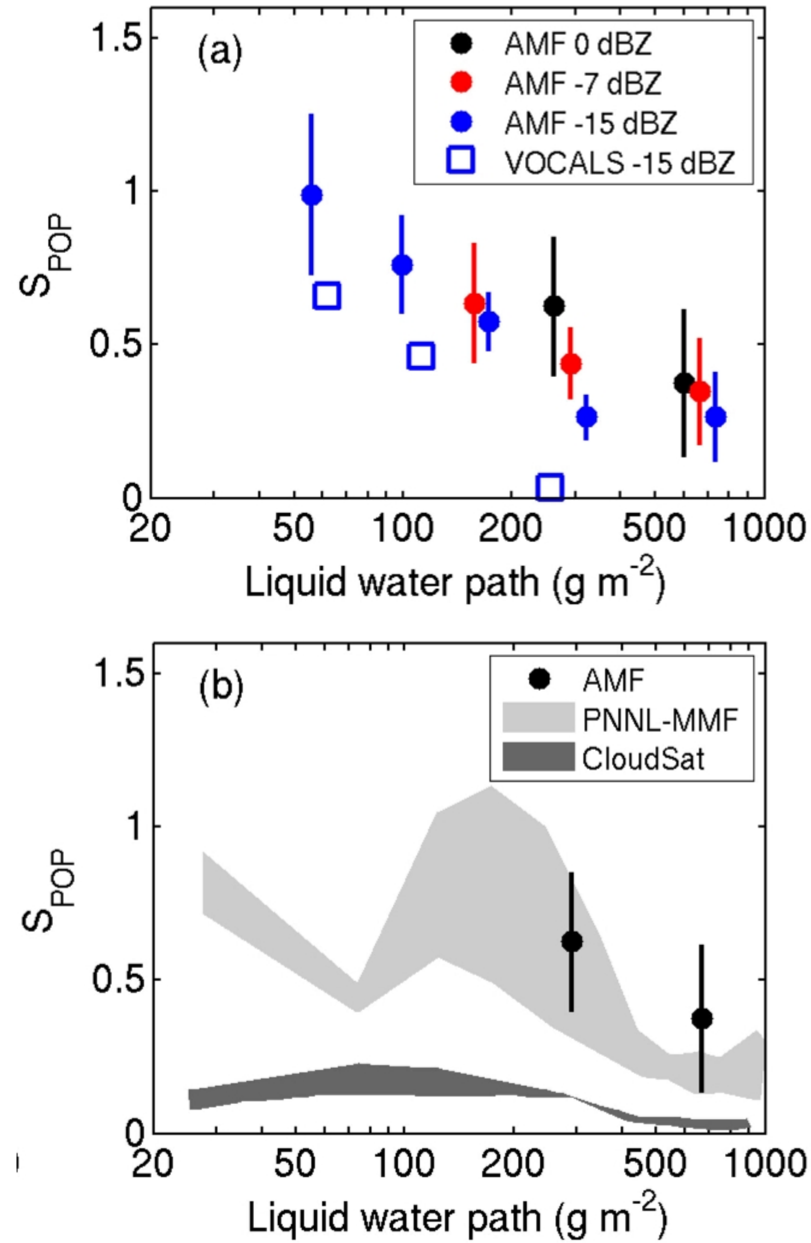
Precipitation susceptibility at the Azores

- The precipitation susceptibility ranges between 0.5 –0.9, and generally agrees with values form simulations and aircraft measurements for LWP < 300 g/m2
- S_{POP} is higher than that from satellites, but similar to those from aircraft obs. and a high-resolution climate model.

Mann et al. (2014, JGR, under review)



Terai et al. (201) for VOCALS; Sorooshian et al. (2009) for LES



Collaborators

Collaborator (initials)	Institution	Role
Andrew Ackerman (AA)	NASA GISS	Provides expertise on process modeling, aerosol-cloud interactions and microphysical process representation in large eddy models
Maike Ahlgrimm (MA)	ECMWF, UK	Provides expertise on the assessment of large scale models using fixed-site and satellite observations
Eduardo Azevedo (EA)	Universidade dos Açores, Portugal	Provides local expertise on Azores weather and climate and fosters connections with the scientific community in the Azores and Portugal
Christine Chiu (CC)	University of Reading, UK	Provides expertise on radiative transfer and cloud microphysical retrievals
Richard Forbes (RF)	ECMWF, UK	Provides expertise on large scale model development of MBL & cloud processes
Virendra Ghate (VG)	Argonne Natl. Laboratory	Provides expertise on the application of radar to Cu and Sc cloud dynamics
Ann Fridlind (AF)	NASA GISS	Provides expertise on process modeling and the integration of observations into model case studies
Anne Jefferson (AJ)	NOAA ESRL	Provides expertise on aerosol measurement
Vincent Larson (VL)	University of Wisconsin, Milwaukee	Provides guidance on higher order closure (CLUBB parameterization) and model assessment/experiment design