Eastern North Atlantic (ENA) Site Science & Infrastructure

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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)
Microphysical-macrophysical process interactions in low clouds occur across scales.
## Remote sensing instrumentation

<table>
<thead>
<tr>
<th>Instrument(s)</th>
<th>Key derived parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RADARS</strong></td>
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</tbody>
</table>
| Ka-band ARM Zenith Radar (KAZR) | (i) Cloud and precipitation vertical structure  
(ii) 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 profile |
| 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 |
| MicrowaveProfiler | (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

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Key derived parameters</th>
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</thead>
<tbody>
<tr>
<td><strong>Balloon-borne Sounding System (BBSS)</strong></td>
<td>(i) Atmospheric profile of temperature, humidity and winds</td>
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<td></td>
<td>(ii) MBL depth</td>
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<td></td>
<td>(iii) Inversion strength</td>
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<tr>
<td><strong>Eddy Correlation Systems (ECOR)</strong></td>
<td>Surface turbulent fluxes of latent and sensible heat</td>
</tr>
<tr>
<td><strong>Surface Meteorological Instruments</strong></td>
<td>Surface temperature, humidity, pressure, winds, precipitation rate (optical and tipping bucket rain gauges, disdrometer)</td>
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<tr>
<td><strong>Surface aerosol observing system</strong></td>
<td>Total aerosol concentration &gt; 10 nm diameter (CN counter);</td>
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<td></td>
<td>CCN spectra at seven supersaturations (nominally 0.1, 0.2, 0.3, 0.5, 0.8, 1, 1.1%)</td>
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<tr>
<td></td>
<td>Aerosol size distribution from 60-1000 nm (UHSAS)</td>
</tr>
<tr>
<td></td>
<td>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;</td>
</tr>
<tr>
<td></td>
<td>Aerosol absorption (PSAP) at three wavelengths (450, 550 and 700 nm) wavelength</td>
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<td></td>
<td>Hygroscopic aerosol size growth (TDMA)</td>
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<td></td>
<td>Aerosol chemical speciation (Aerosol Mass Spectrometer)</td>
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<tr>
<td><strong>Gas tracers</strong></td>
<td>Carbon monoxide/dioxide, nitrous oxide, methane</td>
</tr>
</tbody>
</table>
**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.

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**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

Instruments combinations to generate observational turbulent flux estimates.

<table>
<thead>
<tr>
<th>Flux Profile</th>
<th>Variable</th>
<th>Instruments</th>
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</thead>
<tbody>
<tr>
<td>Thermal</td>
<td>$\theta'$</td>
<td>MWRP, AERI</td>
</tr>
<tr>
<td>Water Vapor</td>
<td>$q'$</td>
<td>RWP</td>
</tr>
<tr>
<td>Condensed Water</td>
<td>$q'_{\text{liquid}}$</td>
<td>SACR, MWR, AERI</td>
</tr>
<tr>
<td>Momentum</td>
<td>$u', v'$</td>
<td>Doppler Lidar, SACR, X-Band</td>
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</table>

**RADARS**
- KAZR (Cloud radar)
- SACR (Scanning cloud radar)
- XSAPR (X-band precip. radar)
- RWP (Radar wind profiler)

**LIDARS**
- DL (Doppler Lidar)
- RL (Raman Lidar)

**PASSIVE INSTRUMENTS**
- MWR (Microwave radiometer)
- AERI (IR spectral radiometer)
- SWS (Shortwave spectrometer)

Cloud and drizzle reflectivity profile, Doppler spectra
Cloud horizontal and vertical structure and in-cloud Doppler winds
Precipitation features and associated horizontal winds
Horizontal virtual temperature and wind profiles

Horizontal and vertical mesoscale wind features using Doppler, turbulence
Aerosol and water vapor profiles in MBL

Liquid water path
Liquid water path in thin clouds. Water vapor profiles
Cloud optical thickness, effective radius/droplet concentration
Precipitation:

- 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).

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

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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.
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

**Observations**

**CAM 5.1**

**GFDL AM3.9**
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
Precipitation susceptibility at the Azores

- The precipitation susceptibility ranges between 0.5 – 0.9, and generally agrees with values from simulations and aircraft measurements for LWP < 300 g/m²
- $S_{\text{POP}}$ 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
<table>
<thead>
<tr>
<th>Collaborator (initials)</th>
<th>Institution</th>
<th>Role</th>
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<tbody>
<tr>
<td>Andrew Ackerman (AA)</td>
<td>NASA GISS</td>
<td>Provides expertise on process modeling, aerosol-cloud interactions and microphysical process representation in large eddy models</td>
</tr>
<tr>
<td>Maike Ahlgrimm (MA)</td>
<td>ECMWF, UK</td>
<td>Provides expertise on the assessment of large scale models using fixed-site and satellite observations</td>
</tr>
<tr>
<td>Eduardo Azevedo (EA)</td>
<td>Universidade dos Açores, Portugal</td>
<td>Provides local expertise on Azores weather and climate and fosters connections with the scientific community in the Azores and Portugal</td>
</tr>
<tr>
<td>Christine Chiu (CC)</td>
<td>University of Reading, UK</td>
<td>Provides expertise on radiative transfer and cloud microphysical retrievals</td>
</tr>
<tr>
<td>Richard Forbes (RF)</td>
<td>ECMWF, UK</td>
<td>Provides expertise on large scale model development of MBL &amp; cloud processes</td>
</tr>
<tr>
<td>Virendra Ghate (VG)</td>
<td>Argonne Natl. Laboratory</td>
<td>Provides expertise on the application of radar to Cu and Sc cloud dynamics</td>
</tr>
<tr>
<td>Ann Fridlind (AF)</td>
<td>NASA GISS</td>
<td>Provides expertise on process modeling and the integration of observations into model case studies</td>
</tr>
<tr>
<td>Anne Jefferson (AJ)</td>
<td>NOAA ESRL</td>
<td>Provides expertise on aerosol measurement</td>
</tr>
<tr>
<td>Vincent Larson (VL)</td>
<td>University of Wisconsin, Milwaukee</td>
<td>Provides guidance on higher order closure (CLUBB parameterization) and model assessment/experiment design</td>
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</tbody>
</table>