Title: Clouds, Aerosol, and Precipitation in the Marine Boundary Layer: Analysis of Results from the ARM Mobile Facility Deployment to the Azores (2009/2010)

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Results to date [end of year 2, updated May 2013]

The project focuses upon dataset analysis and synthesis of datasets from the AMF deployment entitled "Clouds, Aerosols, and Precipitation in the Marine Boundary Layer (CAP-MBL)" at Graciosa Island in the Azores. Wood is serving a PI for this AMF deployment.

The Clouds, Aerosol, and Precipitation in the Marine Boundary Layer (CAP-MBL) experiment used the comprehensive instruments of the ARM Mobile Facility deployment at Graciosa Island in the Azores from May 2009 to December 2010. This platform produced a rich set of coincident and continuous atmospheric measurements of meteorology, aerosols, clouds, precipitation, and radiation in a relatively remote maritime region. Many of the AMF datasets are now available for researchers to explore many important contemporary research questions. Initial studies have focused upon cloud and boundary layer characterization (Rémillard et al. 2012).

Air arriving at the Azores comes from a diversity of sources including clean air from the Arctic, partially polluted air from Canada, and more heavily polluted air from Europe. Analysis of the aerosol extinction and single-scattering albedo has been carried out (Jefferson et al. 2010). These data show interesting seasonal variability, with a springtime minimum in SSA most likely associated with long range transport of anthropogenic pollution from North America.

The ASR projects are allowing us to address many important aerosol questions that are difficult or impossible to understand using satellite or short-term field data alone.

Large scale model performance

The CAP-MBL dataset is also useful for testing global forecast and climate models which are just now including aerosol processes as a standard part of their simulations. The presence

and structure of low clouds, an important and uncertain aspect of climate models, can also be tested at this location over an extended time period. To evaluate GCM performance in simulating Marine Boundary Layer (MBL) processes, such as cloud structure, precipitation, and aerosol-cloud interaction, coincident atmospheric GCM simulations are performed in forecast mode for the period June 2009 – November 2009. Cecile Hannay at NCAR and Yanluan Lin at GFDL have provided forecast model simulations (NCAR CAM 5.1 and GFDL A3p9 GCM respectively) initialized with ECMWF YOTC analysis. Both models include interactive aerosols. Although the model simulations are able to reproduce the thermodynamic fields, winds and the deeper cloud systems associated with midlatitude systems with some fidelity, they are much less skilled in their ability to reproduce the variability in boundary layer cloudiness. We are beginning to compare the model aerosol optical properties with those measured at Graciosa and are finding significant differences. This work is ongoing.

Precipitation

In collaboration with the University of Reading (Ewan O'Connor and Robin Hogan), a radar-lidar combined drizzle dataset has been produced for the entirety of the CAP-MBL deployment. Data are also revealing the dynamic structures within clouds responsible for the production of precipitation. A sensitive new method has been developed to detect the early product of drizzle droplets and subsequent growth and evaporation of drizzle droplets in the cloud and subcloud layers respectively. This has been used to show that drizzle production begins at much lower radar reflectivities in these marine clouds compared to their continental counterparts observed at the ARM SGP site. This is likely related to differences in the aerosol amounts at the two sites. Analysis shows that the precipitation susceptibility scaling with LWP is quite similar to that found over the SE Pacific ocean region during VOCALS.

PI Wood and graduate student Chris Terai are working with Andrew Gettelman and Hugh Morrison [at NCAR] to evaluate microphysical process rates and their impact on precipitation susceptibility in single column versions of climate models (particularly CAM5) and simple heuristic models, using the observational precipitation susceptibility estimates as a target.

Cloud radiative and microphysical properties

Collaborator Qilong Min at SUNY Albany has provided cloud optical thickness and effective radius retrievals from the MFRSR for the entire period of the CAP-MBL deployment. Collaborator Christine Chiu at the University of Reading has provided new cloud optical thickness retrievals from the Narrow Field of View Radiometer (NFOV) for the entire period of the deployment. These will be included in the Cloud Microphysical Properties VAP proposed by the PI that is currently being constructed and evaluated.

Links between column integrated aerosol and in situ CCN properties

Two of the primary science questions of the CAP-MBL project center around the ability to detect interactions between aerosol and cloud properties. Several studies (e.g. Quaas et al., *J. Geophys. Res.*, 2008; Wang et al. *Geophys. Res. Lett.*, 2012) have attempted to quantify aerosol indirect effects on clouds and precipitation globally using spaceborne remote sensing, by using observed variability in aerosol optical depth (AOD) as a proxy for variability in the concentration of cloud condensation nuclei (CCN) being ingested into clouds. We have started a new subproject to use the CAP-MBL and other ASR datasets (VOCALS, SGP, COPS) to quantify the various factors linking AOD to CCN concentrations. A key focus is upon being able to assess the contributions to AOD from accumulation mode aerosol concentration, aerosol size, hygroscopic growth, and aerosol layer depth. Whereas the first of these is the dominant control upon cloud microphysical properties (i.e. cloud droplet concentration) in low clouds, the remainder all potentially contribute significantly in ways that have yet to be quantified well.

Using multiple datasets available from the ARM deployment in the Azores, we are studying this using a combination of rawinsonde relative humidity (RH) profiles, aerosol scattering from dry and wet nephelometers, aerosol backscatter profiles from the MPL, AOD measurements from the CIMEL sunphotometer. To ensure clear skies we are using a number of different cloud products. Our preliminary work, focusing upon the Azores, indicates that relative humidity increases aerosol scattering by a factor that varies from ~2 to 8 times that of its dry scattering properties, with the variability driven largely by ambient RH variability from sounding to sounding, but the variability in how the aerosols grow with RH also contributes non-negligibly.

We are using the in situ aerosol and sounding data to construct AOD from the bottom-up, which we then compare with the measured AOD. While there is considerable noise in the agreement between constructed and measured AOD, we are able to produce good agreement using a compositing approach (using either the seasonal cycle or some other meteorological variable). The next step is to systematically quantify the contributions to AOD variance from the different contributing variables using a bootstrap sampling methodology.

Azores modeling collaboration

PI Wood is helping to provide coordination and ensure appropriate data are available for a number of different modeling projects focused on the Azores region that are currently running or are spinning up. These include:

Andrew Ackerman and George Tselioudis [GISS] – will run high resolution bin microphysics LES to examine detailed microphysical processes observed with WACR and evaluate new parameterization of clouds in the GISS GCM

Steven Krueger [U. Utah] will run cloud system resolving model at low resolution and in 2D to simulate entire deployment period.

Dave Mechem [U. Kansas] will run LES and regional models (COAMPS and/or WRF) for particular cases during deployment to examine relative importance of meteorology and aerosols in driving cloud and precipitation.

Joyce Penner [U Michigan] will compare the single column CAM5 model with a cloud system resolving model for cases with high and low levels of aerosols.

Project summary article for Bulletin of the American Meteorological Society

PI Wood is working with collaborators (M. Wyant, J. Fletcher, C. S. Bretherton**,** M. Miller, J. Rémillard, P. Kollias, E. Luke, A. Jefferson, V. Ghate, G. Tselioudis, D. Mechem, S. E. Yuter, C. Hannay, Y. Lin, R. Palikonda, B. A. Albrecht, W. Wiscombe) from a number of institutions to complete a summary article for the Bulletin of the American Meteorological Society (BAMS) describing the CAP-MBL deployment and some of the key science that has been achieved using data from it. The manuscript is currently in draft form and will be submitted to BAMS during July 2013.

Wood, R., M. Wyant, J. Fletcher, C. S. Bretherton**,** M. Miller, J. Rémillard, P. Kollias, E. Luke, A. Jefferson, V. Ghate, G. Tselioudis, D. Mechem, S. E. Yuter, C. Hannay, Y. Lin, R. Palikonda, B. A. Albrecht, W. Wiscombe, C. Chiu, 2012: Clouds, Aerosol, and Precipitation in the Marine Boundary Layer: An ARM Mobile Facility Deployment. To be submitted to. *Bull. Am. Meteorol. Soc*. July 2013.

Products delivered

Publication describing initial cloud classification and analysis, published in the Journal of Climate: Rémillard, J., P. Kollias, E. Luke, and R. Wood, 2012: Marine boundary layer cloud observations at the Azores**.** *J. Climate,* **25**, 7381-7398.

A paper describing some of the single column model assessment of precipitation susceptibility has been submitted and accepted for discussion: Gettelman, A., Morrison, H., Terai, C. R., and Wood, R.: Microphysical process rates and global aerosol-cloud interactions, *Atmos. Chem. Phys. Discuss.*, **13**, 11789-11825, doi:10.5194/acpd-13-11789-2013, 2013.

Breakout sessions focused upon the CAP-MBL deployment to the Azores have been organized by PI Wood at each of the spring and fall ASR meetings 2009-2012.

The Value Added Products to be constructed as part of the proposed effort are currently being constructed and evaluated.

Additional References:

Kollias, P., J. Remillard, E. Luke and W. Szyrmer, 2011a: Cloud Radar Doppler Spectra in Drizzling Stratiform Clouds. Part I: Forward Modeling and Remote Sensing Applications. J. Geophys. Res., **116, D13201** DOI: **10.1029/2010JD015237.**

Kollias P., W. Szyrmer, J. Remillard and E. Luke, 2011b: Cloud Radar Doppler Spectra in Drizzling Stratiform Clouds. Part II: Observations and Microphysical Modeling of Drizzle Evolution. . J. Geophys. Res., **116**, **D13203** DOI: **10.1029/2010JD015238.**

Wood, R., M. Wyant, J. Fletcher, C. S. Bretherton**,** M. Miller, J. Rémillard, P. Kollias, E. Luke, A. Jefferson, V. Ghate, G. Tselioudis, D. Mechem, S. E. Yuter, C. Hannay, Y. Lin, R. Palikonda, B. A. Albrecht, W. Wiscombe, 2012: Clouds, Aerosol, and Precipitation in the Marine Boundary Layer: An ARM Mobile Facility Deployment. To be submitted to. *Bull. Am. Meteorol. Soc*. July 2013.