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DOE/SC-ARM-16-029

ACAPEX – Ship-Based Ice Nuclei Collections Field Campaign Report

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April 2016

ARM
CLIMATE RESEARCH FACILITY

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Principal Investigators

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Executive Summary

Measurements were sought to evaluate a hypotheses that sea-spray-sourced ice-nucleating particles (INPs) are of biological origin and represent a distinctly different INP population in comparison to long-range-transported desert or urban and regional land-sourced INP, and that the layering of marine within other aerosol layers feeding orographic storms over the mountains of California and the Western United States thereby leads to common and quantifiable scenarios that influence precipitation over the region. Aerosol collections on the National Oceanic and Atmospheric Administration (NOAA) research vessel (RV) *Ronald H. Brown,* for subsequent processing of INP immersion freezing activation temperature spectra and composition analyses, added a valuable measurement component to the ARM Cloud Aerosol Precipitation Experiment (ACAPEX) and related CalWater2 (NOAA) studies for use in parameterizing and modeling the impacts of marine boundary layer and other aerosols on climate and radiation via aerosol indirect effects on mixed-phase clouds. Twenty-five nominally 24-hour collections were made and have been processed for immersion freezing INP number concentrations versus temperature in the mixed-phase cloud temperature regime from -10 to -27°C. The similarity of INP number concentrations compared to typical marine boundary layer values attributed to sea-spray aerosols was noted. Nevertheless, variability of INP concentrations of up to 50 times was noted at individual temperatures over the course of the study. A particular analysis possible with this data set is to examine INP budgets over oceans inside versus outside of atmospheric river conditions. These INP measurements supplemented multiple airborne INP measurements on the ARM Aerial Facility (AAF), and others on the ground during ACAPEX and CalWater2, to provide extensive spatial and temporal analyses of INP immersion freezing spectra during winter storm periods. Future analyses will use thermal sensitivity to examine INP compositions as organic versus inorganic in these marine boundary layer samples. Data set integration is occurring under funding from an Atmospheric System Research (ASR) proposal.

Acronyms and Abbreviations

AAF	ARM Aerial Facility
ACAPEX	ARM Cloud Aerosol Precipitation Experiment
AMF	ARM Mobile Facility
AOS	Aerosol Observing System
AR	atmospheric river
ARM	Atmospheric Radiation Measurement Climate Research Facility
ASR	Atmospheric System Research
C	centigrade
cm	centimeter
CSU	Colorado State University
CW3E	Center for Western Weather and Water Extremes
DOE	U.S. Department of Energy
g	gram
G-1	Gulfstream 1
INP(s)	ice-nucleating particle(s)
IS	Ice Spectrometer (a CSU instrument)
m	meter
MBL	marine boundary layer
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
PI	Principal Investigator
RV	research vessel
SSA(s)	sea spray aerosol(s)
UCSD	University of California, San Diego

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1.0 Background

Ice-nucleating particles (INPs) are required to trigger the formation of first ice crystals in the mixed-phase (liquid and ice) regions of clouds, thereby impacting the transfer of solar and thermal energy through, and precipitation formation processes in, many clouds. Advances in quantifying the number concentrations of INPs in different weather and aerosol scenarios has direct application, via parameterization development, to improving representation of mixed-phase clouds in regional and global climate models. This is the clearest relevance of this research to U.S. Department of Energy (DOE)-Atmospheric Radiation Measurement (ARM) Climate Research Facility objectives and the DOE-Atmospheric System Research (ASR) science plan.

The project reported herein supported INP measurements made during the ARM Cloud Aerosol Precipitation Experiment (ACAPEX) campaign. The overarching ACAPEX campaign is described separately on the ARM website (http://www.arm.gov/campaigns/amf2015apex), with goals to describe the evolution and structure of atmospheric rivers (ARs) from near their regions of development, describe the long-range transport of aerosols in the eastern North Pacific and potential interactions with ARs, and to determine how aerosols from long-range transport and local sources influence cloud and precipitation in the U.S. West Coast where ARs make landfall and post-frontal clouds are frequent. The ACAPEX Ship-Based Ice Nuclei Collections campaign supplemented the second ARM Mobile Facility (AMF2) suite of measurements that were deployed offshore on the NOAA research vessel *Ronald H. Brown*. Aerosol filter collections were made by AMF2 technicians, under our instruction, and these were frozen, shipped, rinsed to remove aerosols and post-processed at Colorado State University (CSU) to determine INP concentrations active via immersion freezing per volume of air collected. The measurements were made using the CSU ice spectrometer (IS) instrument (Hill et al., 2016; Hiranuma et al., 2015) operating in the temperature range from -5 to -27°C. The period of operations was January 14 through February 11, 2015. Collaborators on this study were Sonia Kreidenweis (Colorado State University), the Principal Investigator (PI) on a related National Science Foundation (NSF)-funded research study based at Bodega Bay, California during the same period (January 14 to March 9, 2015), and L. Ruby Leung (Pacific Northwest National Laboratory), as the ACAPEX PI for the AMF2 and AAF Gulfstream 1 (G-1) flights over the region (January 14 to March 9, 2015). A co-Investigator on this study is Thomas Hill, who assisted ship installations and technical training, and then led primary processing of collected filter samples. Ongoing collaborations involve the broader CalWater science team associated with different agency efforts, but especially Dr. F. Martin Ralph and Dr. Andrew Martin, both at the Center for Western Weather and Water Extremes (CW3E) at the University of California, San Diego (UCSD)/Scripps Institution of Oceanography.

The ACAPEX Ship-Based Ice Nuclei Collections data set will have ultimate use in quantifying ice-nucleating particle (INP) budgets in the marine boundary layer more generally, and in ARs specifically, for relation to other critical measurements of the moisture budget, cloud and precipitation processes, and Aerosol Observing System (AOS) aerosol properties. These data, supplemented by INP data sets collected at Bodega Bay (NSF-funded) and on the G-1 (direct DOE funding via subcontract with the AAF) that included both IS measurements and continuous flow diffusion chamber data (DeMott et al., 2015) will be used to define the overall distribution of INPs in storms, and parameterization of their impacts in future numerical modeling studies. Thus, ACAPEX objectives and those of the NOAA-led CalWater2 (http://www.esrl.noaa.gov/psd/calwater/) campaign will be supported with these data.

Integration of various data sets at the time of this report is occurring under separate Atmospheric Systems Research funding (DE-SC0014354), and additional NSF-supported analyses are planned.

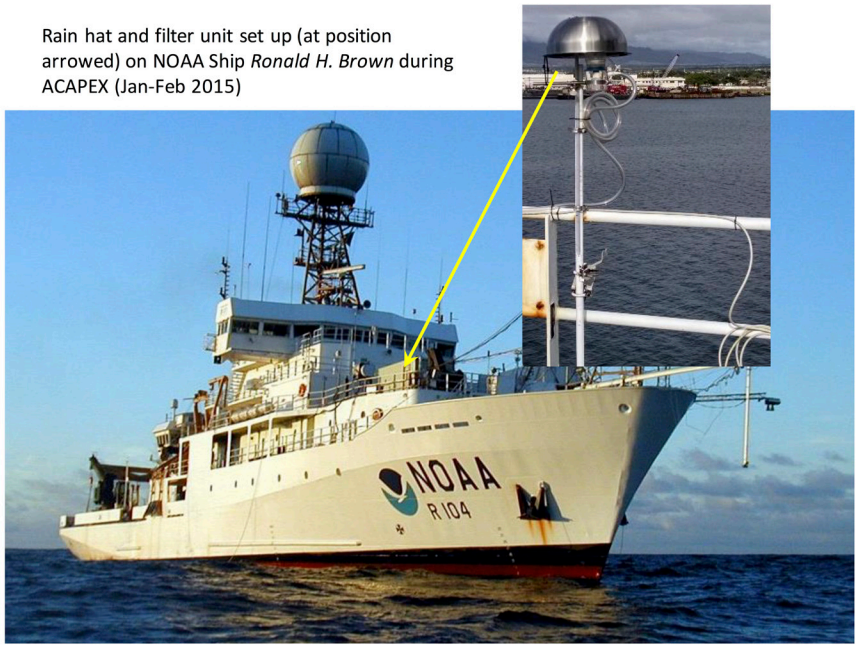

Figure 1. Mounting of filter samplers on the *Ronald H. Brown*.

2.0 Notable Events or Highlights

A comprehensive data set was obtained, including the first ever INP measurements from air within and across ARs over ocean regions. Analyses of these data are continuing, and first results are given below.

On a few days, a perfect seal may not have been achieved for the filter samplers, as inferred by somewhat larger recorded sample volumes. These cases are noted in the archive.

3.0 Lessons Learned

There were no significant issues for this study. We learned, again, that high-quality results can be obtained for our INP filter samples through basic training of AMF personnel in their collection, handling and storage. By meeting the ship at port at the end of the study, we were able to confirm the ability pack samples on dry ice and succeed in shipping them frozen to our laboratory.

4.0 Results

Preliminary data plots are shown in Figures 2 and 3. INP number concentrations measured during the ACAPEX cruise showed a range of a 50 factor variation at any given temperature. This variability may

reflect higher emissions from sea-spray production in certain periods such as an AR, rainout influences, influences of different ocean biology as the ship moved into shallower regions closer to shore, influences of long-range transport of continental aerosols, and other factors. Figure 3 demonstrates that some of this variability occurred on single-day time scales, which will bear more careful analyses. To initially place the data in some context, information from two other recent studies are shown in Figure 2. First, the average values and upper and lower bounding region for INP number concentrations attributed to sea spray aerosols (SSA) in laboratory experiments and selected actual marine boundary layer (MBL) sampling, normalized for MBL total particle numbers of 150 cm^{-3}, are shown based on DeMott et al. (2015). The ACAPEX ship-based data set fits largely within the same bounds as defined in DeMott et al. (2015), albeit focused within the lower range of values attributed to SSA production. Also shown in Figure 2 is the lower bounding curve of INP number concentrations found in a number of studies analyzing INP numbers per volume of precipitation, converted to INP numbers per volume of air through a standardizing assumption of a cloud liquid water content of 0.4 g m^{-3} (Petters and Wright, 2015). This analysis demonstrates that INP numbers in air over the Pacific during ACAPEX were also typically lower than have been found to be scavenged from clouds by precipitation in other locales.

Analyses that will be pursued using this data set include use of AOS data to relate INP number concentrations to aerosol number in different size ranges, and aerosol surface area for the purpose of constraining parameterizations for INPs in the marine boundary layer. Relation of INP spectral data to other AMF-2 data sets such as remote sensing of cloud properties may also be insightful. Finally, comparison to and integration with other INP data sets in ACAPEX and CalWater2 can also be used to describe the spatial characteristics of INP populations within and around winter storms, to give insights into the role of INPs in precipitation processes. Many of these analyses have begun under present funding from the DOE ASR program.

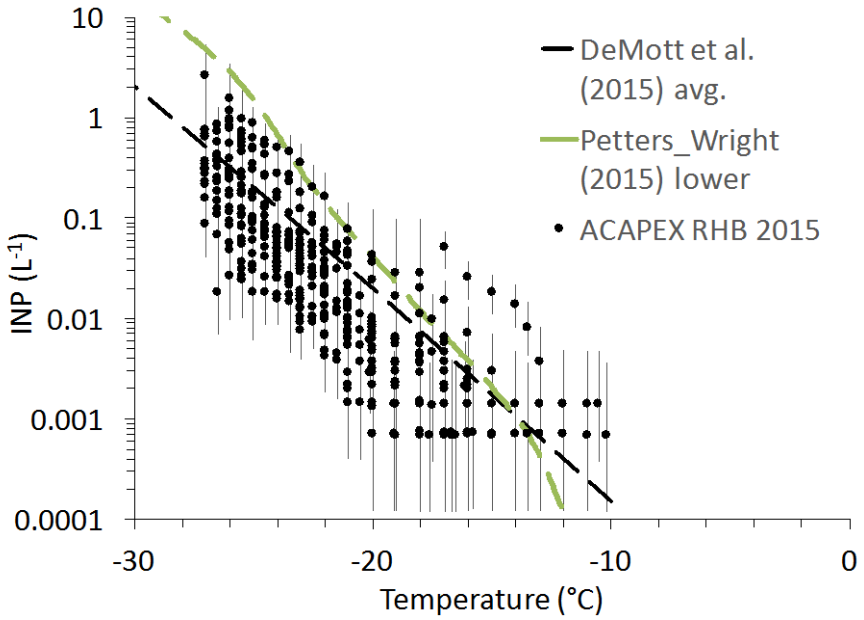

Figure 2. All INP temperature spectra for the campaign, absent days in, or close to, port. The INP number concentration spectra attributed to sea-spray aerosols for average marine boundary layer conditions from DeMott et al. (2015) is shown as the long-dashed black line with

bounds given by the gray shading. The lower bound of INP spectra for precipitation samples from Petters and Wright (2015), based on converting for a cloud liquid water content of 0.4 g m^{-3}, is given by the dashed green line.

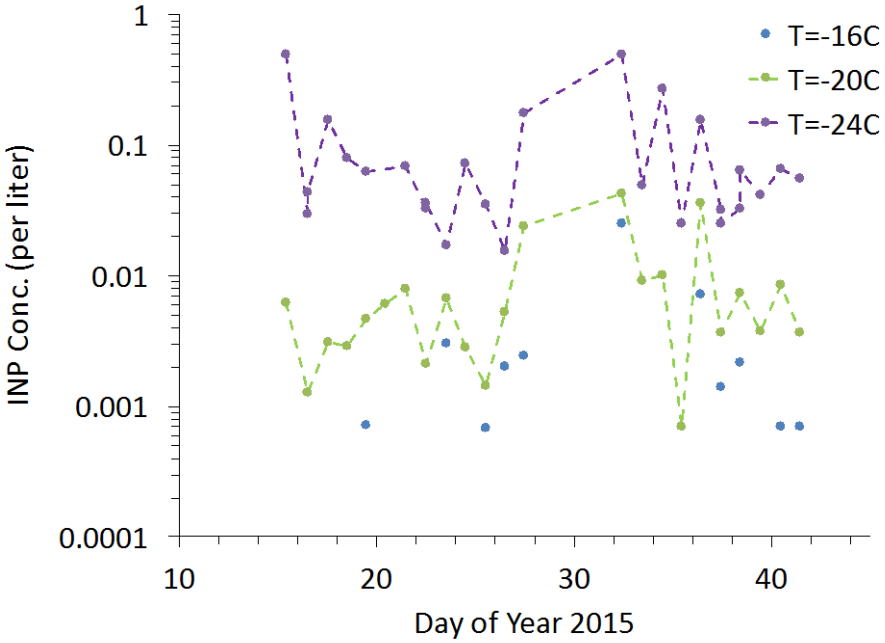

Figure 3. Timeline of INP number concentration at two temperatures for the cruise period. Points are connected at two temperatures despite data gaps in a few periods, notably during the entry to port in San Francisco in the middle of the study.

5.0 Public Outreach

No major public outreach efforts occurred with this project, but the ACAPEX study is presently a highlight fixture on the PI's website (https://chem.atmos.colostate.edu/PJDeMott/research.html).

6.0 ACAPEX Ship-Based Ice Nuclei Collections Publications

6.1 Journal Articles/Manuscripts

None to report at this time. In process.

6.2 Meeting Abstracts/Presentations/Posters

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