Final Report Chief Scientist for Atmospheric Radiation Measurement (ARM) Aerial Vehicle Program (AVP)

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As outlined in the proposal to act as Chief Scientist for the AVP program, the major responsibilities of the PI were identified as 1) the formulation of campaign plans, 2) the representation of AVP in various scientific communities inside and outside of ARM and the associated working groups, 3) the coordination and selection of the relative importance of the three different focus areas (routine observations, IOPs, instrument development program), 4) the examination and quality control of the data collected by AVP, and 5) providing field support for flight series. This report documents the accomplishments in each of these focus areas for the 3 years of funding for the grant that were provided.

Formulation of Campaign Plans: The PI created a flight planning document for the Indirect and Semi-Direct Aerosol Campaign (ISDAC), a field campaign for which he was appointed lead-PI in April 2008. This document outlines flight profiles flown by the National Research Council of Canada Convair during ISDAC, and their relation to the science objectives that were also summarized in the ISDAC Science Overview Document (SOD), a documented to which the PI made major contributions. The PI also developed the operations plan that governed the timing for the weather briefings and go/no-go decisions in the field, and described the roles of the planning and management teams. The basic flight profiles and the meteorological conditions in which they were flown were also summarized in this document. There were a number of different mission types that were flown during ISDAC: missions or components of missions flown in the vicinity of Barrow; components of missions flown during transits to and from Barrow; and components of missions that involved coordinated flying with other aircraft in the vicinity of Barrow. The flight patterns in the vicinity of Barrow involved constant altitude legs above, below and within cloud, ramped ascents and descents through cloud, spiral flight patterns over the North Slope of Alaska (NSA) ground site, and missed approaches over the Barrow airport. The transit flights involved flight level legs through cirrus or enhanced aerosol layers. The Flight Planning document summarized the science questions that are being addressed with each of the flight scenarios and identified the key instrumentation needed for each. This document was very helpful in formulating flight plans in the field.

The PI worked heavily with Dr. Andrew Vogelmann of Brookhaven National Laboratory, on the creation of a science operations plan for the Routine ARM Aerial Vehicle Program (AVP) Cloud with Low Optical Water Depths (CLOWD) Optical Radiative Operations (RACORO), a field campaign conducted between January to June 2009 for which the PI a major role. This document overviews RACORO, lists the RACORO science questions and then goes onto define the instruments and measurements needed to address these questions, along with the sampling strategy, flight scheduling and execution and field program management. The PI used the experience he gained in previous AVP (ISDAC, CLASIC, TWP-ICE, M-PACE) and non-AVP campaigns

(BAMEX, INDOEX, AIRS-II) to determine the optimum strategy for the flight scheduling and execution and for the sampling strategy.

The PI also worked heavily with Dr. Jay Mace and the rest of the Small Particles in Cirrus (SPARTICUS) steering committee to draft a science operations plan for the SPARTICUS campaign. This document overviews the need for making measurements of the microphysical properties of cirrus, and then describes the science questions and priorities, the instruments and platforms to be used to take the measurements needed to answer these questions, and finally outlines the flight tracks that will be followed to acquire the needed data. In particular, the PI contributed the assets section of this document.

Representation of the AVP in various scientific communities inside and outside of ARM: The PI has been heavily involved in representing the AVP through organization and participation in meetings. The PI has organized a day-long dedicated ISDAC session that was conducted at the ARM cloud modeling and aerosol properties joint working group meeting in Boulder, Colorado in October 2009. In addition, the PI organized the ISDAC special session at the ARM Science Team meeting in Louisville, Colorado. The PI has served as co-organizer of a special session at the Annual Meeting of the American Geophysical Union in San Francisco in December 2009 entitled "Composition of the Arctic Atmosphere: Sources, Transport, Chemistry, and Impacts on Clouds and Climate," a session where the preliminary findings from ISDAC are being presented. The PI also has presented the ISDAC findings at the American Meteorological Society Polar Conference and at a special seminar at the Chinese Meteorological Academy in Beijing, China. The PI presented a presentation on scientific findings from past ARM airborne flight campaigns at the International Conference on Airborne Research for the Environment in Toulouse France in 2010 and at the International Conference on Antarctic Clouds in Columbus Ohio in 2010. The PI also assisted Dr. Williamson in his presentation to the AQRS (CENR Air Quality Research Subcommittee). Finally, Dr. McFarquhar has also participated in various on-line/telecom meetings for RACORO and SPARTICUS.

Along with Beat Schmid, the Chief Scientist represented the AVP on the former ARM Science and Infrastructure Steering Committee (SISC) until 2009. Further, he represented the AVP at all 4 former working groups of ARM during the annual meetings (modeling, aerosols, clouds and radiation) and at the ISDAC science team meeting in November in Lansdowne, Virginia in 2008. The Chief Scientist has also represented the AVP at the Spring AGU meeting in Ft. Lauderdale, Florida, in 2008 discussing the science applications that could be addressed with uninhabited aerospace vehicles (UAS), at the ISDAC planning meeting in Ottawa, Canada, and attended the IMB planning meeting in July 2008 in Washington, DC. However, the biggest role in representing AVP was leading and coordination a workshop on advances in airborne instrumentation for measuring aerosols, clouds and state parameters held in Champaign, Illinois in October 2008. For this meeting, the Chief Scientist took care of all local logistics, solicited presentations from many speakers and set the program. The meeting was immensely successful with over 40 attendees from many agencies and countries. A publication for

BAMS has been submitted based on the outcome of this workshop. In addition, the results of this workshop have been used in setting instrument priorities for the ARM AVP program in an upcoming call for proposals to mature/harden instruments, funding which is being made available in FY2011. The PI also organized and led the ISDAC science team meeting, setting the program for this meeting.

Coordinating the Examination and Quality Control of the AVP data: The PI has worked extensively with many different ISDAC PIs to ensure that the ISDAC data are being quality controlled and placed in the archive. A specific emphasis of his has been on the quality control and archival of the cloud microphysics data. In particular, the PI's group has been responsible for the archival and processing of the CDP, CAS, CIP and CSI data during ISDAC, and has recently provided the one-second size distributions from the 2DC and 2DP to the ISDAC archive in collaboration with scientists from Environment Canada. Further, graduate student Robert Jackson traveled to Environment Canada to work with Dr. Alexei Korolev to work on the removal of the drifting offset and drift of the Nevzorov probe data, something necessary to do in order to get useable bulk water contents from this probe.

Further, postdoctoral associated Junshik Um and the PI visited the University of Manchester in September 2009 to calibrate the Cloud Particle Imager (CPI). Although the CPI was not originally intended to provide size distributions for ISDAC and TWP-ICE, a recent study by the University of Manchester group (UMIST) suggested that the CPI may be able to accurately measure size distributions given sufficient large averaging times. Paul Connolly of UMIST generated size distributions by determining a scaling factor for their CPI using their calibration facility at Manchester. The scaling factor determined for the Manchester CPI is not applicable to the DOE CPI because the Manchester CPI is a Version 1 CPI, whereas the DOE CPI is a Version 2 CPI. SPEC has found that the Version 2 CPI is more sensitive to the detection of small particles than the Version 1 CPI so any scaling factor developed to correct for the measurement of small particles in Version 1 would overestimate small particles when applied to Version 2. Thus, we derived the scaling factor for the DOE Version 2 CPI during our visit to Manchester, and are now in the process of applying the scaling factor to the TWP-ICE and ISDAC data so that size distributions can be generated and placed in the archive. Dr. Junshik Um has been extensively interacting with Dr. Paul Connolly of the University of Manchester to develop a publication to describe this work.

The PI's group has also been concentrating on quality controlling the cloud microphysical data collected during the RACORO field campaign. This has involved working with Haf Jonson from CIRPAS on comparing bulk water contents measured by the Gerber and hot-wire probes, against liquid water contents derived from the size-resolved distributions measured by the CAS, FSSP, 1DC and 2DC probes. Based on these comparisons, some problems with the probes were identified early on in the field campaign and were then rectified, allowing a quality data to be collected. Since the end of the project, graduate student Hee-Jung Yang has been further inter-comparing the measurements from the different probes, including those made by the 2DS, with the ultimate aim of trying to construct the best estimate of size distributions over the

complete range of particles. Such distributions can be useful for calculating bulk quantities that are needed for applications using the data.

Field Support for Flight Series: During RACORO, the PI spent eight weeks serving as either PI or assistant PI on the development of flight plans for the daily flights. This involved choosing which of the pre-set flight profiles would be flown and setting take-off times after listening to daily weather briefings. Similarly, the PI spent eight weeks serving as either PI or assistant PI during the SPARTICUS field project and spent four weeks in Fairbanks, Alaska serving as PI for the ISDAC project. The PI also participated in flight planning exercises for SPARTICUS and RACORO.

Planning of Future Field Campaigns: The PI played an integral role in planning future field campaigns, such as SPARTICUS, ISDAC and RACORO, when he was the chief scientist for AVP. The accomplishments of those field projects is described above. Further, the PI provided guidance and assistance on the tasks associated with the acquisition of cloud microphysical instrumentation as part of the ACRF Recovery Act.

Documents

Ghan, S., B. Schmid, J. Hubbe, C. Flynn, A. Laskin, A. Zelenyuk, D. Cziczo, C. Long, G. McFarquhar, J. Verlinde, J. Harrington, W. Strapp, P. Liu, A. Korolev, A. McDonald, M Wolde, A. Fridlind, T. Garrett, G. Mace, G. Kok, S. Brooks, D. Collins, D. Lubin, P. Lawson, M. Dubey, M. Shupe, S. Xie, D. Turner, Q. Min, D. Turner, Q. Lin, E. Mlawer and D. Mitchell, 2007: Science Overview Document: Indirect and Semi-Direct Campaign (ISDAC) April 2008. DOE/SC-ARM-0705, Available from http://www.arm.gov/publications/programdocs/doe-sc-arm-0705.pdf

Vogelmann, A., G. McFarquhar, J. Ogren. D. Turner, G. Feingold, and C. Long, 2008: RACORO: Science and Operations Plan.

McFarquhar, G.M., S. Ghan, A. Korolev, P. Liu, W. Strapp, J. Verlinde and M. Wolde, 2008: ISDAC Flight Planning Document. Available from http://www.atmos.uiuc.edu/~mcfarq/isdac_flightplan.pdf

Papers:

Fridlind, A.M., A.S. Ackerman, G.M. McFarquhar, G. Zhang, M.R. Poellot, P.J. DeMott, A.J. Prenni, and A.J. Heymsfield, 2007: Ice properties of single layer stratocumulus during the Mixed-Phase Arctic Cloud Experiment (MPACE). Part II: Model results. *J. Geophys. Res.*, **112**, D24202, doi:10.1029/2007JD008646.

McFarquhar, G.M., J. Um, M. Freer, D. Baumgardner, G.L., Kok and G. Mace, 2007: The importance of small ice crystals to cirrus properties: Observations from the Tropical Western Pacific International Cloud Experiment (TWP-ICE). *Geophys. Res. Lett.*, **34**, L13803, doi:10.1029/2007GL029865.

McFarquhar, G.M., G. Zhang, M.R. Poellot, G.L. Kok, R. McCoy, T. Tooman, and A.J. Heymsfield, 2007: Ice properties of single layer stratocumulus during the Mixed-Phase Arctic Cloud Experiment (MPACE). Part I: Observations. *J. Geophys. Res.*, **112**, D24202, doi:10.1029/2007JD008646.

Um, J.S., and G.M. McFarquhar, 2007: Single-scattering properties of aggregates of bullet rosettes in cirrus. *J. Appl. Meteor. Climat.*, **46**, 757-775.

Verlinde, J., J.Y. Harrington, G.M. McFarquhar, V.T. Yannuzzi, A. Avramov, S. Greenberg, N. Johnson, M.R. Poellot, J.H. Mather, D.D. Turner, B.D. Zak, T.P. Tooman, A.J. Prenni, G.L. Kok, E.W. Eloranta, M.D. Ivey, C.P. Bahrmann, K. Sassen, P.J. DeMott and A.J. Heymsfield, 2007: The Mixed-Phase Arctic Cloud Experiment (M-PACE). *Bull. Amer. Meteor. Soc.*, **88**, 205-221.

Barnard, J.C., C.N. Long, E.I. Kassianov, S.A. McFarlane, J.M. Comstock, M. Freer and G.M. McFarquhar, 2008: Development and evaluation of a simple algorithm to find cloud optical depth with emphasis on thin ice clouds. *Open Atmos. Sci. J.*, **2**, 46-55.

Liou, K.N., Y. Gu, Q. Yue and G. McFarguhar, 2008: On the correlation between ice water content and ice crystal size and its application to radiative transfer and general circulation models. *Geophys. Res. Lett*., **35**, L13805, doi:10.1029/2008GL033918.

Luo, Y., K.-M. Xu, H. Morrison and G. McFarquhar, 2008: Arctic mixed-phase clouds simulated by a cloud resolving model: Comparison with ARM observations and sensitivity to microphysics parameterizations. *J. Atmos. Sci.*, **65**, 1285-1303.

Luo, Y., H. Morrison, G.M. McFarquhar, Z. Wang and G. Zhang, 2008: Multi-layer Arctic mixed phase clouds simulated by a cloud resolving model: comparison with ARM observations and sensitivity experiments. J. Geophys. Res., **113**, D12208, doi:10.1029/2007JD009563.

May, P.T., J.H. Mather, G. Vaughan, C. Jacob, G.M. McFarquhar, K.N. Bower, 2008: The Tropical Warm Pool International Cloud Experiment (TWPICE). *Bull. Amer. Meteor. Soc.*, **89,** 629-645.

Mitchell, D.L., P. Rasch, D. Ivanova, G.M. McFarquhar and T. Nousianen, 2008: The impact of controversial small ice crystals on GCM simulations. *Geophys. Res. Lett.*, **35**, L09806, doi:10.1029/2008GL033552.

Morrison, H., J.O. Pinto, J.A. Curry and G.M. McFarquhar, 2008: Sensitivity of modeled arctic mixed-phase stratocumulus to cloud condensation and ice nuclei over regionally-varying surface conditions. *J. Geophys. Res.*, **113**, D05203, doi:10.1029/2007JD008729.

Sednev, I., S. Menon, G. McFarquhar, and A.D. Del Genio, 2008: Simulating mixed-phase Arctic stratus clouds: sensitivity to ice initiation mechanisms. *Atmos. Chem. Phys.*, **8**, 11755-11819.

Shupe, M.D., P. Kollias, O.G. Persson and G.M. McFarquhar, 2008: Vertical motions in Arctic mixed-phase stratus. *J. Atmos. Sci*., **65**, 1304-1322.

Klein, S.A., R. McCoy, H. Morrison, A. Ackerman, A. Avramov, G. de Boer, M. Chen, J. Cole, A. D. DelGenio, M. Falk, M. Foster, A. Fridlind, J.-C. Golaz, T. Hashino, J. Harrington, C. Hoose, M. Khairoutdinov, V. Larson, X. Liu, Y. Luo, G. McFarquhar, S. Menon, R. Neggers, S. Park, K. von Salzen, J.M. Schmidt, I. Sednev, B. Shipway, M. Shupe, D. Spangenberg, Y. Sud, D. Turner, D. Veron, G. Walker, Z. Wang, A. Wolf, S. Xie, K.-M. Xu, G. Yang and G. Zhang, 2008: Intercomparison of model simulations of mixed-phase clouds observed during the ARM Mixed-Phase Arctic Cloud Experiment. Part I: Single layer cloud. *Quart. J. Roy. Meteor. Soc.*, **135**, 979-1002.

Morrison, H., R. McCoy, S. Klein, S. Xie, Y. Luo, A. Avramov, M. Chen, J. Cole, M. Falk, M. Foster, A. Del Genio, J. Harrington, C. Hoose, M. Khrairoutdinov, V. Larson, X. Liu, G. McFarquhar, B. Shipway, M. Shupe, Y. Sud, D. Turner, D. Veron, G. Walker, Z. Wang, A. Wolf, K.-M. Xu, F. Yang and G. Zhang, 2008: Intercomparison of model simulations of mixed-phase clouds observed during the ARM Mixed-Phase Arctic Cloud Experiment, Part II: Multi-layered cloud. *Quart. J. Roy. Meteor. Soc.*, **135**, 1003-1019.

Prenni, A.J., P.J. DeMott, D.C. Rogers, S.M. Kreidenweis, G.M. McFarquhar, G. Zhang and M.R. Poellot, 2009: Ice nuclei characteristics from M-PACE and their relation to ice formation in clouds. *Tellus B*, **61**, 436-448.

Um, J., and G.M. McFarquhar, 2009: Single-scattering properties of aggregates of plates from TWP-ICE. *Quart. J. Roy. Meteor. Soc.,* **135**, 291-304.

van Diedenhoven, B., A.M. Fridlind, A.S. Ackerman, E.W. Eloranta, and G.M. McFarquhar, 2009:An evaluation of ice formation in large eddy simulations of supercooled Arctic stratocumulus using ground-based lidar and cloud radar. *J. Geophys. Res.*, **114**, D10203, doi:10.1029/2008JD011198.

Fen, J., J.M. Comstock, M. Ovchinnikov, S. A. McFarlane, G. McFarquhar and G. Allen, 2010: Tropical anvil characteristics and water vapor of the tropical tropopause layer (TTL): Impact of heterogeneous and homogeneous freezing parameterizations. *J. Geophys. Res.*, **115**, D12201, doi:10.1029/2009JD012696.

McFarquhar, G.M., B. Schmid, A. Korolev, J.A. Ogren, P.B. Russell, J. Tomlinson, D.D. Turner, and W. Wiscombe, 2011: Airborne instrumentation needs for climate and atmospheric research. *Bull. Amer. Meteor. Soc.*, **92**, 1193-1195.

McFarquhar, G.M., S. Ghan, J. Verlinde, A. Korolev, J. W. Strapp, B. Schmid, J. M. Tomlinson, M. Wolde, S. D. Brooks, D. Cziczo, M. K. Dubey[7], J. Fan[2], C. Flynn, I. Gultepe, J. Hubbe, M. K. Gilles, A. Laskin, P. Lawson, W. R. Leaitch, P. Liu, X. Liu, D. Lubin, C. Mazzoleni, A.-M. Macdonald, R. C. Moffet, H. Morrison, M. Ovchinnikov, M. D. Shupe, D. D. Turner, S. Xie, A. Zelenyuk, K. Bae, M. Freer, and A. Glen, 2010: Indirect and Semi-Direct Aerosol Campaign (ISDAC): The impact of arctic aerosols on clouds, *Bull. Amer. Meteor. Soc.*, **92**, 183-201.

Morrison, H., P. Zuidema, G.M. McFarquhar, A. Bansemer, and A.J. Heymsfield, 2011: Observed exponential snow particle size distributions in the Arctic during SHEBA/FIRE.ACE and MPACE: Comparison of shallow and deep mixed-phase clouds. *J. Atmos. Sci.,* In press.

Nousiainen, T., H. Lindqvist, G.M. McFarquhar, and J. Um, 2011: Quasi-spherical ice crystals in tropical cirrus. *J. Atmos. Sci.*, In press.

Protat, A., G.M. McFarquhar, J. Um, and J. Delanoe, 2011: Obtaining best estimates for the microphysical and radiative properties of tropical ice clouds from TWP-ICE in-situ microphysical observations, *J. Appl. Meteor. Clim.*, **50**, 895-915.

Um, J., and G.M. McFarquhar, 2011: Dependence of the single-scattering properties of small ice crystals on idealized shape models. *Atmos. Phys. Chem. Dis.*, **11**, 3159-3171.