FINAL REPORT: *Investigations of Mixed-Phase Cloud Microphysical, Radiative, and Dynamical Processes*

Grant number: DE-SC0007005

Principle Investigator: Matthew Shupe

Funding Period: August 2011 – July 2014

Accomplishments

Accomplishments to over the course of this grant can be broken into four categories:

1) *Mixed-phase Cloud Retrieval and Dataset Development*

Work during this project focused on evaluating and improving retrievals of cloud dynamical and microphysical properties from Doppler cloud radar measurements. Under prior DOE funding, a retrieval was developed whereby vertical air motions are derived from radar Doppler spectra measurements using cloud liquid droplets as tracers for air motion. That retrieval has been evaluated and improved using collocated wind profiler and aircraft measurements at the ARM North Slope of Alaska (NSA) facility. In the same retrieval framework, the turbulent dissipation rate can be derived from the temporal variance of radar measured Doppler velocities. A thorough evaluation of this retrieval (Shupe et al. 2012) was conducted using aircraft measurements from the Mixed-Phase Arctic Cloud Experiment (MPACE) and tethered balloon measurements from the Arctic Summer Cloud Ocean Study (ASCOS). In each case, the evaluation platforms were flown above a ground-based radar allowing for comparisons of measured versus retrieved dissipation rates. Results from the two different experiments are broadly consistent, indicating root mean squared differences of a factor of 4-6, with about half of the differences being due to spatial and temporal differences in the measurements. A netCDF dissipation rate product for important campaign periods, including uncertainty estimates, was produced and submitted to the ARM archive as a PI product.

Cloud macrophysical and phase data sets produced for many years at the NSA Barrow and Atqasuk facilities under prior ASR funding were published in a pair of journal articles (Shupe et al. 2011; Shupe 2011). The first documents cloud occurrence fraction, boundaries, vertical distribution, and persistence at the ARM facilities relative to other Arctic atmospheric observatories. The second expands on this information by distinguishing the cloud occurrence by phase at a subset of the Arctic facilities with the appropriate instrumentation for determining cloud phase. That paper demonstrates an important finding that the processes responsible for cloud phase partitioning appear to be relatively consistent among multiple sites and observed differences in cloud phase occurrence are primarily driven by differences in large-scale meteorological parameters. The information on cloud phase distributions was used to evaluate climate model simulations from the NCAR Community Climate System Model #4 (de Boer et al. 2012).

Cloud microphysical properties data sets were produced from ground-based, multi-sensor measurements at the NSA site and other similar Arctic observatories using the ShupeTurner cloud retrieval suite (Shupe et al. 2014a). These products have been used in model evaluation studies examining cloud-radiation interactions (Du et al. 2011), entrainment rates and ice nucleation (Fridlind et al. 2012), the response of clouds to aerosol concentrations (Birch et al. 2012), the variability of cloud properties at different Arctic sites (Cox et al. 2014), and the representation of clouds in reanalyses (de Boer et al. 2014). The PI participated in the ASR QUICR Focus Group's evaluation of cloud retrieval algorithms (Zhao et al. 2012) by submitting the ShupeTurner product to the ARM archive for inclusion in the ARM Cloud Retrieval Ensemble Dataset (ACRED). The algorithm was also evaluated using radiative closure experiments and compared with the standard ARM MICROBASE product (Shupe et al. 2014a).

2) *Observational Process Studies*

Observational analyses have focused on the coupling state of low-level Arctic stratiform clouds at the NSA site. The coupling state refers to the energetic coupling, or lack thereof, between the surface and the cloud layer, usually accompanied by vertical mixing processes. Briefly, the turbulent energy required for forming clouds can be contributed from surface turbulent heat fluxes, cloud top radiative cooling, wind shear, and/or frontal dynamics. Some combination of these impacts leads to cloud formation, and their relative roles help to determine the coupling state. Ultimately, the coupling state has important implications for cloud formation, longevity, and cloud-aerosol interactions among other things.

The analyses conducted here focused on the MPACE and ISDAC (Indirect and Semi-Direct Aerosol Campaign) intensive observational experiments that occurred at the NSA site in 2004 and 2008, respectively. These experiments offered nice perspectives on cloud processes in spring versus autumn where properties of the clouds, surface, and coupling state are distinct. An expanded analysis examined the coupling state in stratiform clouds observed at NSA over the course of three years with high quality observations (2004, 2008, 2009). Lastly, the analysis was expanded to include measurements from a similar deployed on an icebreaker in Arctic sea ice for a few weeks in late summer 2008. Using these data it was found that surface-coupled clouds occur most frequently in all seasons of the year except for winter, when decoupled clouds occur more often. Coupled clouds generally occur with warmer surface temperatures and when the cloud base height is lower. Additionally, coupled clouds tend to have more liquid water than de-coupled clouds, a feature that can have important implications for surface radiative effects of clouds. In de-coupled clouds, vertical profiles of turbulent dissipation rate generally show a minimum between the cloud base and surface, clearly signifying the energetic de-coupling, while the coupled clouds have a relatively constant or increasing amount of turbulence below the cloud. These results are published in Shupe et al. (2013, 2014b). Additionally, it was found that the coupling state impacts the vertical distribution of aerosols (Shupe et al. 2013) and interacts in complex ways with cloud top moisture inversions (Sedlar and Shupe 2014; Sotiropoulou et al. 2014).

Lastly, using knowledge gained about cloud microphysical-dynamical interactions the PI contributed to many collaborative studies on topics including: the role of aerosols on ice production in mixed-phase clouds (Lance et al. 2011), the role of cloud liquid water in ice onset in mixed-phase clouds (de Boer et al. 2011), the potential limiting effect of very low aerosol concentrations on cloud formation (Mauritsen et al. 2011), the frequent occurrence of moisture inversions associated with Arctic low-level clouds (Sedlar et al. 2012), a review of Arctic mixed-phase cloud persistence processes

(Morrison et al. 2012), and observing atmosphere structure using dropsondes from unmanned aircraft (Intrieri et al. 2014).

3) *Regional and Large-Eddy Simulation (LES) Modeling of Mixed-Phase Processes*

Modeling work conducted as part of this project involves using the Weather Research and Forecasting (WRF) model framework in two different and complementary ways to examine mixed-phase cloud processes: a nested regional perspective and a traditional LES perspective. For the former, the model is run with five nested domains, such that the large outer domain covers a significant portion of the Arctic Basin and can resolve mesoscale influences on clouds. Inner domains telescope into the Barrow region and the inner-most domain was pushed to resolutions as fine as 50m in the horizontal. We use up to 8m vertical resolution near the cloud layer to resolve key vertical processes such as cloud top radiative cooling, turbulence, and entrainment. This perspective is in some ways preferable to the traditional LES approach, as it is able to capture the interactions between large-scale and cloud-scale processes. This nested approach was used to examine in great detail a case from ISDAC (Solomon et al. 2011). Specifically, we used energy and moisture budget analyses to understand the role of moisture inversions near cloud top for sustaining Arctic mixed-phase clouds. The model showed how cloud-top entrainment can moisten the cloud layer, as opposed to lower latitude stratocumulus clouds where entrainment dries the cloud, leading to longer life times.

More recently, we implemented the model physics from our nested WRF-LES simulations into a traditional LES style with periodic boundary conditions. This approach allows us to examine the relative role of mesoscale feedbacks on cloud-scale processes versus cloud-scale processes alone. This traditional approach allowed us to examine Arctic mixed-phase stratocumulus clouds from the perspective of a mixed-layer model, as has been done for sub-tropical stratocumulus. We used a series of idealized simulations to study the impact of moisture sources from both above and below a cloud-driven mixed layer and the impacts these have on the cloud lifetime and persistence processes (Solomon et al. 2014). This approach, since it allows us to effectively control for (and/or eliminate) horizontal advective tendencies, makes it easier to perform budget analyses for both total water and moist static energy within the cloud-atmosphere system. With this approach we were able to maintain a cloud that was decoupled from the surface for longer than a day and explore the partitioning of moisture among the three water phases and how this is driven by cloud turbulent mixing and sedimentation processes.

Lastly, we used our LES modeling tools to participate in the ISDAC model intercomparison project (Ovchinnikov et al. 2014). Using simulations from numerous collaborators we examined the role that ice particle size distribution assumptions play in the ability to simulate Arctic mixed-phase clouds.

4) Storm Peak Validation Experiment (StormVEx) analyses

The PI collaborated with other StormVEx investigators to study cloud and precipitation processes in a mountainous region of the central Rocky Mountains. Two papers were published that examine scanning radar measurements (Matrosov et al. 2012; Marchand et al. 2013). These demonstrate how angular scans of radar depolarization ratio contain information on the habit of falling ice crystal and document the enhancement of radar backscatter at zenith viewing when oriented ice crystals are present can be significant. Both papers have implications for understanding radar measurements and interpreting them relative to ice crystal shape. The PI also worked with colleagues to study the spatial distribution of mixed-phase clouds and their properties relative to the mountain barrier during StormVex (Dorsi et al. 2014) and the spatial structure of mountain waves associated with orographic forcing (Kingsmill et al. 2014). These studies combined measurements from a research aircraft and ground-based observations.

Service to ARM

- Co-Chair of the Cloud Life Cycle Working Group (2008-present)
- Member of ASR Science and Infrastructure Steering Committee (2008-present)
- Member of the ARM Climate Research Facility Board (2009-2011, 2013)
- Co-I on StormVex program.
- Co-lead of Arctic Aerosol-Cloud Interactions (AACI) interest group
- Member of ARM-ASR Radar Science Committee

Papers and Products:

Data products produced under this grant include:

1) A 2-year version of the ShupeTurner MICROBASE product has been submitted to the ARM archive as part of the ARM Cloud Retrieval Ensemble Dataset (ACRED), and provided to members of the ARM-BBHRP community and individual modeling efforts. This product includes time-height fields of cloud liquid and ice microphysical properties and a cloud type classification mask.

2) Ten-year cloud occurrence and macrophysical properties data sets have been produced for Barrow, Atqasuk, and other Arctic atmospheric observatories. This product includes cloud occurrence, vertical distribution, boundaries, and total thickness for a number of available instruments and a best estimate of each parameter based on an optimal combination of the individual measurements. Data sets are all available on the Cooperative Arctic Data and Information Service (CADIS) archive.

3) Cloud vertical velocity and turbulent dissipation rate product has been submitted to the ARM archive as a PI product. This product covers the extended periods for the MPACE and ISDAC campaigns and includes information on uncertainties.

This project supported the principle investigator’s work on a number of studies regarding mixed-phase clouds and in various related collaborations with ARM and related scientists that have contributed to the following peer-reviewed publications and conference/meeting presentations over the period of 2011-2014.

Peer-Reviewed Publications

Birch, C. E., and Coauthors (including M. D. Shupe), 2012: Modelling atmospheric structure, cloud and their response to CCN in the Central Arctic: ASCOS case studies. *Atmos. Chem. Phys.*, 12, 3419-3435.

Cox, C. J., D. D. Turner, P. M. Rowe, M. D. Shupe, and V. P. Walden, 2014: Cloud microphysical properties retrieved from downwelling infrared radiance measurements made at Eureka, Nunavut, Canada (2006-2009). *J. Appl. Meteor. Clim.*, 53, 772-791.

de Boer, G., H. Morrison, M. D. Shupe, and R. Hildner, 2011: Evidence of liquid dependent ice nucleation in high-latitude stratiform clouds from surface remote sensors. *Geophys. Res. Lett*., 38, L01803, doi:10.1029/2010GL046016.

de Boer, G., W. Chapman, J. Kay, B. Medeiros, M.D. Shupe, S. Vavrus, J. Walsh, 2012: Characterization of present-day Arctic Atmosphere in CCSM4. *J. Clim.*, 25, 2676-2695.

de Boer, G., M. D. Shupe, and Coauthors, 2014: Near-surface meteorology during the Arctic Surface Cloud Ocean Study (ASCOS): Evaluation of reanalyses and global climate models. *Atmos. Chem. Phys*., 14, 427-445, doi:10.5194/acp-14-427-2014.

Dorsi, S. W., M. D. Shupe, P. O. G. Persson, D. E. Kingsmill, and L. M. Avallone, 2014: Phase-specific characteristics of wintertime clouds across a midlatitude mountain range. *Mon. Wea. Rev*., submitted.

Du, P., E. Girard, A.K. Bertram, and M. D. Shupe, 2011: Modeling of the cloud and radiation processes observed during SHEBA. *Atmos. Res*., 101, 911-927.

Fridlind, A. M., B. van Diedenhoven, A. S. Ackerman, A. Avramov, A. Mrowiec, H. Morrison, P. Zuidema, and M. D. Shupe, 2012: A FIRE-ACE/SHEBA case study of mixed-phase Arctic boundary-layer clouds: Entrainment rate limitations on rapid primary ice nucleation processes. *J. Atmos. Sci*., 69, 365-389.

Intrieri, J. M., and Coauthors, 2014: Global Hawk dropsonde observations of the Arctic atmosphere obtained during the Winter Storms and Pacific Atmospheric Rivers (WISPAR) field campaign. *Atmos. Meas. Tech*., 7, 3917-3926.

Kingsmill, D. E., P. O. G. Persson, S. Haimov, and M. D. Shupe, 2014: Mountain waves and orographic precipitation in a northern Colorado winter storm. *Quart. J. Roy. Meteor. Soc*., submitted.

Lance, S., M. D. Shupe, and Coauthors, 2011: CCN as a modulator of ice processes in Arctic mixed-phase clouds. *Atmos. Chem. Phys*., 11, 8003-8015.

Marchand, R., G. G. Mace, A. G. Hallar, I. B. McCubbin, S. Y. Matrosov, and M. D. Shupe, 2013: Enhanced radar backscattering due to oriented ice particles at 95-GHz during StormVex. *J. Atmos. Oceanic Technol.*, 30, 2336-2351.

Matrosov, S. Y., G. G. Mace, R. Marchand, M. D. Shupe, A. G. Haller, and I. B. McCubbin, 2012: Influence of ice hydrometeor habits on scanning polarimetric cloud radar measurements. *J. Atmos. Oceanic Technol*., 29, 989-1008.

Mauritsen, T., and Coauthors (including M. Shupe), 2011: An Arctic CCN-limited cloud-aerosol regime. *Atmos. Chem. Phys.*, 11, 165-173.

McFarquhar, G. M., and Coauthors (including M. Shupe), 2011: Indirect and Semi-Direct Aerosol Campaign (ISDAC): The impact of Arctic aerosols on clouds. *Bull. Amer. Meteor. Soc.*, 92, 183 - 201.

Morrison, H., G. de Boer, G. Feingold, J. Harrington, M. D. Shupe, and K. Sulia, 2012: Resilience of persistent Arctic mixed-phase clouds. *Nature Geoscience*, 5, 11-17.

Ovchinnikov, M., and Coauthors (including M. Shupe and A. Solomon), 2014: Intercomparison of large-eddy simulations of Arctic mixed-phase clouds: Importance of ice size distribution assumptions. *J. Adv. Model. Earth Systems*, 6, 223-248.

Sedlar, J., and Coauthors (including M. Shupe), 2011: A transitioning Arctic surface energy budget: the impacts of solar zenith angle, surface albedo and cloud radiative forcing. *Clim. Dyn.*, 37, 1643-1660.

Sedlar, J., M. Shupe, M. Tjernstrom, 2012: On the relationship between thermodynamic structure, cloud top, and climate significance in the Arctic. *J. Climate*, 25, 2374-2393.

Sedlar, J. and M. D. Shupe, 2014: Characteristic nature of vertical motions observed in Arctic mixed-phase stratocumulus. *Atmos. Chem. Phys.*, 14, 3461-3478.

Shupe, M. D., V. P. Walden, E. Eloranta, T. Uttal, J. R. Campbell, S. M. Starkweather, and M. Shiobara, 2011: Clouds at Arctic Atmospheric Observatories, Part I: Occurrence and macrophysical properties. *J. Appl. Meteor. Clim.*, 50, 626-644.

Shupe, M. D., 2011: Clouds at Arctic Atmospheric Observatories, Part II: Thermodynamic phase characteristics. *J. Appl. Meteor. Clim.*, 50, 645-661.

Shupe, M. D., I. Brooks, and G. Canut, 2012: Evaluation of turbulent dissipation rate retrievals from Doppler cloud radar. *Atmos. Meas. Tech.*, 5, 1375-1385.

Shupe, M. D., P. O. G. Persson, I. M. Brooks, M. Tjernström, J. Sedlar, T. Mauritsen, S. Sjogren, and C. Leck, 2013: Cloud and boundary layer interactions over the Arctic sea-ice in late summer. *Atmos. Chem. Phys.*, 13, 9379-9400, doi:10.5194/acp-13-9379-2013

Shupe, M. D., D. D. Turner, A. Zwink, M. M. Theiman, M. J. Mlawer, and T. R. Shippert, 2014a: Deriving Arctic cloud microphysics at Barrow: Algorithms, results, and radiative closure. *J. Appl. Meteor. Clim.*, submitted.

Shupe, M. D., O. Persson, A. Solomon, G. de Boer, 2014b: Seasonal and structural influences on the coupling between Arctic mixed-phase stratiform clouds and the surface. *J. Atmos. Sci.*, in preparation.

Solomon, A., M. D. Shupe, P.O.G. Persson, and H. Morrison, 2011: Moisture and dynamical interactions maintaining decoupled Arctic mixed-phase stratocumulus in the presence of a humidity inversion. *Atmos. Chem. Phys.*, 11, 10127-10148.

Solomon, A. S., M. D. Shupe, P. O. G. Persson, H. Morrison, T. Yamaguchi, P. M. Caldwell, and G. de Boer, 2014: The sensitivity of springtime Arctic mixed-phase stratocumulus clouds to surface layer and cloud-top inversion layer moisture sources. *J. Atmos. Sci*., 71, 574-595, doi:10.1175/JAS-D-13-0179.1.

Sotiropoulou, G., J. Sedlar, M. Tjernström, M. D. Shupe, I. M. Brooks, and P. O. G. Persson, 2014: The thermodynamic structure of summer Arctic stratocumulus and the dynamic coupling to the surface. *Atmos. Chem. Phys*., 14, 12573-12592.

Zhao, C., and Coauthors (including M. D. Shupe), 2012: Towards understanding of differences in current cloud retrievals of ARM ground-based measurements. *J. Geophys. Res.*, 117, D10206, doi:10.1029/2011JD016792.

Conferences/Meetings

Cadeddu, M. P., D. D. Turner, M. D. Shupe, R. Bennartz, and V. P. Walden, 2013: Statistical properties of cloud liquid water path at Barrow, Alaska and at the Greenland Summit Station. *4th Annual ASR Science Team Meeting*, Potomac, MD, 18-21 March.

Canut, G., and Coauthors (including M. Shupe), 2012: Turbulence structure of the central Arctic boundary layer. *AMS 20th Symposium on Boundary Layers and Turbulence*. Boston, MA, 9-13 July.

Chirokova, G., and Coauthors (including M. Shupe), 2012: Vertical distribution of liquid water in mixed-phase clouds from in situ ground and airborne measurements during simultaneous CAMPS and StormVEx field campaigns. *AMS 15th Conference on Mountain Meteorology*. Steamboat Springs, CO, 20-24 August.

de Boer, G., O. Persson, and M. D. Shupe, 2012: Understanding the impact of Arctic cloud regimes on the surface energy budget: Observations from IPY and beyond. *International Polar Year 2012 Conference*, Montreal, Canada, 22-27 April.

de Boer, G., H. Morrison, A. Solomon, O. Persson, M. Shupe, 2012: Relationships between large-scale meteorological conditions and low liquid-containing Arctic clouds Abstract A23C-0242 presented at 2012 Fall Meeting, AGU, San Francisco, CA., 3-7 Dec.

de Boer, G., T. Garrett, M. Shupe, and C. Zhao, 2013: Revised estimates of aerosol indirect effects in thin, liquid-containing Arctic clouds. Abstract A41D-0090 presented at 2013 Fall Meeting, AGU, San Francisco, CA., 9-13 Dec.

de Boer, G., T. Garrett, M. Shupe, and C. Zhao, 2014: Additional insight into aerosol indirect effects in thin, liquid-containing Arctic clouds. *5th Annual ASR Science Team Meeting*, Potomac, MD, 10-13 March.

Kingsmill, D. E., P. O. G. Persson, S. Haimov, and M. D. Shupe, 2014: Mountain waves and orographic precipitation in a Northern Colorado winter storm. *AMS 16th Conference on Mountain Meteorology*.

Kollias, P., and Coauthors (including M. Shupe), 2012: Scanning cloud radar observations at the ARM sites. Abstract A33Q-06, 2012 Fall Meeting, AGU, San Francisco, CA., 3-7 Dec.

Mace, G., G. Hallar, I. McCubbin, M. Shupe, S. Matrosov, A. Sedlacek, C. Long, L. Avallone, 2012: The Storm Peak Lab Cloud Property Validation Experiment: Overview and emerging science. 3rd *Annual ASR Science Team Meeting*, Arlington, VA, 12-16 Mar.

Matrosov, S., G. Mace, R. Marchand, M. Shupe, G. Hallar, I. McCubbin, 2012: Potential of using scanning polarimetric cloud radar measurements for identifying habits of ice hydrometeors and estimating their shapes. 3rd *Annual ASR Science Team Meeting*, Arlington, VA, 12-16 Mar.

Matrosov, S., G. Mace, R. Marchand, M. Shupe, G. Hallar, and I. McCubbin, 2012: Potential of using scanning polarimetric cloud radar measurements for identifying habits of ice hydrometeors and estimating their shapes. *7th European Conf. on Radar in Meteorology and Hydrology,* Toulouse, France, 25-29 June.

Morrison, H., G. de Boer, G. Feingold, J. Harrington, M. D. Shupe, and K. Sulia, 2011: Self-organization and resilience of Arctic mixed-phase clouds. *WCRP Open Science Conference,* Denver, CO, 24-28 October.

Morrison, H., G. de Boer, G. Feingold, J. Harrington, M. D. Shupe, and K. Sulia, 2012: Self-organization and resilience of Arctic mixed-phase clouds. IPY 2012 Conference, Montreal, Canada, 22-27 April.

Ovchinnikov, M., A. Ackerman, G. de Boer, A. Fridlind, J. Harrington, S. Ghan, A. Korolev, A. Lock, G. McFarquhar, H. Morrison, B. Shipway, and M. Shupe, 2012: ISDAC LES intercomparison: Case setup and preliminary results. 3rd *Annual ASR Science Team Meeting*, Arlington, VA, 12-16 March.

Ovchinnikov, M, and Coauthors (including M. Shupe, A. Solomon), 2013: Intercomparison of LES of Arctic mixed-phase clouds. *4th Annual ASR Science Team Meeting*, Potomac, MD, 18-21 March.

Persson, P.O.G., G. de Boer, A. Solomon, M. Shupe, and C. Wheeler, 2012: Synoptic/mesoscale modulation of surface radiation over Arctic sea ice. Abstract A11K-0198 presented at 2012 Fall Meeting, AGU, San Francisco, CA., 3-7 Dec.

Persson, O, A. Solomon, G. de Boer, M. Shupe, and C. Wheeler, 2013: Boundary-layer impacts and modulation of liquid water in wintertime Arctic clouds. European Geosciences Union, General Assembly 2013, Vienna, Austria, 7-12 April.

Persson, POG, A Solomon, M Shupe, G de Boer, C Wheeler, 2013: Interactions between clouds, atmospheric boundary-layer, and snow-covered sea ice during SHEBA winter. *Proc. 12th Conf. on Polar Met. and Ocean.*, AMS, Seattle, WA, 29 April – 2 May.

Pleavin, T. D., I. M. Brooks, J. S. Dobbie, M. D. Shupe, M. Tjernström, P. O. G. Persson, and B. J. Brooks, 2012: A large eddy simulation study of Arctic boundary-layer cloud. AMS 20th Symposium on Boundary Layers and Turbulence. Boston, MA, 9-13 July.

Seefeldt, M.W., M. Tice, J. J. Cassano, and M. D. Shupe, 2012: Evaluation of WRF Radiation and microphysics parameterizations for use in the polar regions. International Commission on Polar Meteorology workshop, Boulder, CO, 12 July.

Seefeldt, M. W., M. Tice, J. J. Cassano, and M. D. Shupe, 2013: Evaluation of WRF radiation and microphysics parameterizations for use in the Arctic. *Proc. 12th Conf. on Polar Met. and Ocean.*, AMS, Seattle, WA, 29 April – 2 May

Shupe, M. D., P. O. G. Persson, A. Solomon, I. Brooks, G. Canut, 2012: Turbulence profiles and cloud-surface coupling in Arctic stratiform clouds. 3rd *Annual ASR Science Team Meeting*, Arlington, VA, 12-16 March.

Shupe, M.D., P.O.G. Persson, A. Solomon, 2012: Cloud-surface coupling in Arctic stratiform clouds. *Int'l Polar Year 2012 Conference*, Montreal, Canada, 22-27 April.

Shupe, M. D., 2012: Persistent supercooled liquid water: A process-level perspective on Arctic stratiform cloud. University of Wisconsin – Madison, Atmospheric and Ocean Sciences Department colloquium, Madison, Wisconsin, 8 October (invited presentation).

Shupe, M. D., 2012: A process-level perspective on Arctic clouds. 1st Pan-Global Atmosphere System Studies (GASS) Conference, Boulder, Colorado, 10-14 September (invited presentation).

Shupe, M.D., 2012: A 15-year legacy of cloud and atmosphere observations in Barrow, Alaska. Abstract GC14A-07 presented at 2012 Fall Meeting, AGU, San Francisco, CA., 3-7 Dec.

Shupe, M. D., P.O.G. Persson, A. Solomon, G. de Boer, 2013: Arctic cloud-driven mixed layers and surface coupling state. *4th ASR Science Team*, Potomac, MD, 18-21 March.

Shupe, MD, POG Persson, A Solomon, 2013: Arctic cloud-driven mixed layers and surface coupling state. *Proc. 12th Conf. on Polar Met. and Ocean.*, AMS, Seattle, WA, 29 April – 2 May.

Shupe, M.D., P.O.G. Persson, A. Solomon, and G. de Boer, 2013: Arctic cloud-driven mixed layers and surface coupling state. Abstract A11E-0100 presented at 2013 Fall Meeting, AGU, San Francisco, CA., 9-13 Dec.

Solomon, A., M. D. Shupe, P.O.G. Persson, and H. Morrision, 2012: The role of cloud-top humidity inversions in the maintenance of Arctic mixed-phase stratocumulus. IPY 2012 Conference, Montreal, Canada, 22-27 April.

Solomon, A., M. Shupe, O. Persson, H. Morrison, 2012: Moisture & dynamical interactions maintaining decoupled Arctic mixed-phase stratocumulus in the presence of a humidity inversion. 16th Int'l Conf. Clouds and Precipitation, Leipzig, Germany, 30 July – 3 Aug.

Solomon, A., M. Shupe, O. Persson, H. Morrison, 2012: The maintenance of decoupled Arctic stratocumulus. Int'l Commission on Polar Meteorology, Boulder, CO, 12 July.

Solomon, A., M. Shupe, O. Persson, H. Morrison, and G. de Boer, 2012: The maintenance of decoupled Arctic stratocumulus. Abstract A31G-01 presented at 2012 Fall Meeting, AGU, San Francisco, CA., 3-7 Dec.

Solomon, A., M. D. Shupe, P. O. G. Persson, 2013: The sensitivity of Arctic stratocumulus to moisture sources in the subcloud and cloud top inversion layers. *4th Annual ASR Science Team Meeting*, Potomac, MD, 18-21 March.

Solomon, A., M. Shupe, O. Persson, 2013: The sensitivity of Arctic stratocumulus to moisture sources in the subcloud and cloud top inversion layers. *Proc. 12th Conf. on Polar Met. and Ocean.*, AMS, Seattle, WA, 29 April – 2 May.

Solomon, A., M. D. Shupe, and P. O. G. Persson, 2014: The differing impact of local and remote moisture sources on cloud formation and the surface energy budget at Summit, Greenland. *European Geosciences Union*. Abstract EGU2014-8033

Sotiropoulou, G., J. Sedlar, M. Tjernstrom, M. Shupe, I. Brooks, O. Persson, 2014: The thermodynamic structure of summer Arctic stratocumulus and the dynamic coupling to the surface. *European Geosciences Union*, abstract EGU2014-1171.

Tjernstrom, M., I. M. Brooks, C. E. Birch, G. Canut, P. O. G. Persson, M. D. Shupe, T. Mauritsen, and J. Sedlar, 2012: Central Arctic low-level cloud and boundary-layer processes. *International Polar Year 2012 Conference*, Montreal, Canada, 22-27 April.

Tjernstrom, M.K., M. Kapsch, T. Mauritsen, R. G. Graverson, J. Sedlar, M. Shupe, 2012: Role of longwave radiation for the variability of sea ice. Abstract A11K-0196 presented at 2012 Fall Meeting, *American Geophysical Union*, San Francisco, CA, 3-7 Dec.

Turner, D., M. D. Shupe, 2011: Using ground-based remote sensors to investigate Arctic clouds and processes. *Gordon Conf. Radiation & Climate*, Waterville, ME, 9-10 July.

Zhao, C., and Coauthors (including M.D. Shupe), 2011: Understanding differences in current cloud retrievals of ARM ground-based measurements. Abstract A23F-02 presented at 2011 Fall Meeting, AGU, San Francisco, CA,5-9 Dec.