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Principal Investigator: Dr. R. Paul Lawson

Team Members: Dr. Sara Lance, Dr. Mo Qixu

“Synthesis of in-situ microphysical measurements with remote retrievals and models”

Executive Summary:

The comprehensive suite of in-situ cloud microphysical instruments that were operated onboard the Environment Canada Convair-480 during ISDAC 2008 provided a rich dataset for investigating the effect of cloud microphysics on cloud radiative properties and the effects of aerosol on clouds. The combination of CDP, 2D-S and 2D-P probes allowed for quantitative measurement of particle sizes spanning the range from 1 μm to > 1 mm and particle concentrations spanning the range from 10^{-5} to 10^5 L^{-1} . The faster electronics of the 2D-S probe compared to older instruments allowed for more accurate sizing and concentration measurements. The reduced effect of ice shatter artifacts as a result of modifications to the 2D-S probe tips and the ability to identify ice particle shatter events using particle interarrival times was particularly valuable for accurate analysis of particles in the size range <400 μm . Furthermore, the use of a sophisticated multi-dimensional algorithm for estimating particle mass on a particle by particle basis, using the particle perimeter, cross sectional area, length and perpendicular width, was applied for 2D-S data for the first time. Altogether, these state-of-the-art measurements and analysis techniques provided the most accurate and detailed glimpse to date of mixed-phase Arctic stratus.

These detailed in-situ measurements were used to model the radiative properties of mixed-phase clouds with distinct microphysical properties, to determine the importance of the cloud bulk properties (e.g. liquid water content and ice water content) and cloud microphysical properties (including ice particle size and habit) on radiative fluxes in the Arctic. High resolution images of ice particles obtained using the Cloud Particle Imager (CPI) were used to identify ice particle habit for input into a new Modified Anomalous Diffraction Approximation (MADA) model to evaluate the effect of real particle shapes on the ratio of forward and backward scattering at different wavelengths. This was the first time the MADA code was used for evaluation of mixed-phase clouds. Ice and liquid particle size distributions were characterized from the combination of cloud probe instruments and the results were input into the MADA code to simulate the cloud effective radius, extinction coefficient and single scatter albedo. The combined liquid and ice radiative properties at multiple altitude levels were then input into a radiative transfer model to determine shortwave and longwave radiative fluxes. This analysis is still ongoing, but results will be submitted to the journal *Atmospheric Chemistry and Physics* in the coming months.

Original Hypotheses:

One of our main questions is whether the cloud microphysical properties (e.g. ice particle size and shape) can have a significant effect on mixed-phase cloud radiative properties, or if the liquid properties (e.g. volume mean droplet diameter and liquid water content) dominate the radiative effects of the cloud. Other questions are: 1) how does aerosol pollution affect cloud phase transitions? 2) how is the best way to define cloud effective radius for mixed-phase clouds? 3) How does the issue of ice particle shattering affect measured cloud size distributions?

Objectives/accomplishments:

- 1) **We proposed to:** “Produce individual water drop and ice particle size distributions in ISDAC mixed-phase clouds, and compute derived properties, including liquid water content, ice water content, total water content, extinction, effective drop radius, effective ice particle radius and optical depth”. **Accomplishment of this goal is demonstrated by:** the poster presentation given during the 2012 ASR Science Team Meeting in Arlington, VA (copy provided in Appendix B) and in the scientific paper Lance et al. (2013) to be submitted to the journal *Atmospheric Chemistry and Physics* (draft provided in Appendix C).
- 2) **We proposed to:** “Compare in-situ microphysical measurements with ISDAC measurements of aerosols, including cloud condensation nuclei and ice forming nuclei, to assess the indirect effect of aerosols on mixed-phase Arctic clouds”. **Accomplishment of this goal is demonstrated by:** the scientific paper Jackson et al. (2012) (abstract attached in Appendix A).

- 3) **We proposed to:** “Compute vertical profiles of short wave and long wave optical properties (extinction, single scattering albedo, asymmetry parameter) for the ice and water portions of the clouds by inputting CPI cloud particle shapes and 2D-S particle size distributions into the Mitchell et al. (2006) modified anomalous diffraction approximation (MADA) code”. **Accomplishment of this goal is demonstrated by:** Lance et al. (2013) to be submitted to the journal *Atmospheric Chemistry and Physics* (draft provided in Appendix C).
- 4) **We proposed to:** “Compute vertical profiles of radiative forcing and heating rates using two-stream radiative forcing code (Toon et al. 1989)”. **Accomplishment of this goal is demonstrated by:** Lance et al. (2013) to be submitted to the journal *Atmospheric Chemistry and Physics* (draft provided in Appendix C).
- 5) **We proposed to:** “Provide in situ data (microphysical, optical, and radiative properties described above) to ARM-funded collaborator Jay Mace to compare with remote retrievals.” **This has been done.**
- 6) **We proposed to:** “Provide in situ mixed-phase microphysical data to ARM-funded collaborators Wojciech Grabowski and Hugh Morrison in a format that can be used with their new bulk two-moment mixed-phase microphysical model (Morrison and Grabowski 2008).” **This has been done.**
- 7) **We proposed to:** “Collaborate with Greg McFarquhar’s and Walter Strapp’s groups (if funded under this call) to support their analysis of CPI and 2D-S ISDAC data.” **Accomplishment of this goal is demonstrated by:** the scientific paper Jackson et al. (2012) (abstract attached in Appendix A).
- 8) **We proposed to:** “Collaborate with David Mitchell and Phil Rasch (if funded under this call) to provide microphysical data that supports their development of parameterizations for the NCAR (GCM) Community Atmosphere Model version 4 (CAM4).” **Accomplishment of this goal is demonstrated by:** the scientific paper Mitchell et al. (2011) (abstract attached in Appendix A).

Products:

- 1) Presentation of preliminary results of mixed-phase cloud microphysical properties at the ASR meeting in Arlington, VA March, 2012 (poster presentation below).
- 2) Archiving of all data from 2D-S and CPI probes installed on the WB-57F and DC-8 research aircraft.
- 3) Analysis of ISDAC data and contribution to four published journal articles plus another journal article currently in preparation for submission (abstracts given below).

Appendix C: Scientific Paper Abstracts

Modeling optical properties and radiative effects of stratiform Arctic mixed-phase clouds using comprehensive in-situ cloud microphysical measurements from ISDAC 2008

Sara Lance¹, R. Paul Lawson¹, David Mitchell² and Eric Jensen³

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Abstract

In this study, in-situ measurements of individual ice particles and water droplets from multiple independent cloud particle probes have been combined to infer separate ice and water particle size distributions, using observations of stratiform Arctic mixed-phase clouds from the 2008 Indirect and Semi-Direct Aerosol Campaign (ISDAC). Shortwave and longwave optical properties (extinction, single scatter albedo and asymmetry parameter) are then calculated using a version of the modified anomalous diffraction approximation (MADA) code, which has been altered to account for both the liquid and ice phases. A two-stream radiative transfer model is then used to compute vertical profiles of radiative forcing and heating rates.

Citation: S. Lance, R. P. Lawson, D. Mitchell, and E. Jensen (2012), Modeling optical properties and radiative effects of stratiform Arctic mixed-phase clouds using comprehensive in-situ cloud microphysical measurements from ISDAC 2008, in preparation for submission to Atmos. Chem. Phys.

Effects of ice particles shattering on the 2D-S probe

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Abstract

Recently, considerable attention has been focused on the issue of large ice particles shattering on the inlets and tips of cloud particle probes, which produces copious ice particles that can be mistakenly measured as real ice particles. Currently two approaches are being used to mitigate the problem: (1) Based on recent high-speed video in icing tunnels, probe tips have been designed that reduce the number of shattered particles that reach the probe sample volume, and (2) Post processing techniques such as image processing and using the arrival time of each individual particle. This paper focuses on exposing suspected errors in measurements of ice particle size distributions due to shattering, and evaluation of the two techniques used to reduce the errors. Data from 2D-S probes constitute the primary source of the investigation, however, when available comparisons with 2D-C and CIP measurements are also included. Korolev et al. (2010b) report results from a recent field campaign (AIIE) and conclude that modified probe tips are more effective than an arrival time algorithm when applied to 2D-C and CIP measurements. Analysis of 2D-S data from the AIIE and SPARTICUS field campaigns shows that modified probe tips significantly reduce the number of shattered particles, but that a particle arrival time algorithm is more effective than the probe tips designed to reduce shattering. A large dataset of 2D-S measurements with and without modified probe tips was not available from the AIIE and SPARTICUS field campaigns. Instead, measurements in regions with large ice particles are presented to show that shattering on the 2D-S with modified probe tips produces large quantities of small particles that are likely produced by shattering. Also, when an arrival time algorithm is applied to the 2D-S data, the results show that it is more effective than the modified probe tips in reducing the number of small (shattered) particles. Recent results from SPARTICUS and MACPEX show that 2D-S ice particle concentration measurements are more consistent with physical arguments and numerical simulations than measurements with older cloud probes from previous field campaigns. The analysis techniques in this paper can also be used to estimate an upper bound for the effects of shattering. For example, the additional spurious concentration of small ice particles can be measured as a function of the mass concentration of large ice particles. The analysis provides estimates of upper bounds on the concentration of natural ice, and on the remaining concentration of shattered ice particles after application of the post-processing techniques. However, a comprehensive investigation of shattering is required to quantify effects that arise from the multiple degrees of freedom associated with this process, including different cloud environments, probe geometries, airspeed, angle of attack, particle size and type.

Citation: R. P. Lawson (2011), Effects of ice particles shattering on the 2D-S probe , Atmos. Meas. Tech., 4, 1361-1381, doi:10.5194/amt-4-1361-2011.

Understanding effective diameter and its application to terrestrial radiation in ice clouds

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Abstract

The cloud property known as “effective diameter” or “effective radius”, which in essence is the cloud particle size distribution (PSD) volume at bulk density divided by its projected area, is used extensively in atmospheric radiation transfer, climate modeling and remote sensing. This derives from the assumption that PSD optical properties can be uniquely described in terms of their effective diameter, D_e , and their cloud water content (CWC), henceforth referred to as the D_e -CWC assumption. This study challenges this assumption, showing that while the D_e -CWC assumption appears generally valid for liquid water clouds, it appears less valid for ice clouds in regions where (1) absorption is not primarily a function of either the PSD ice water content (IWC) or the PSD projected area, and (2) where wave resonance (i.e. photon tunneling) contributes significantly to absorption. These two regions often strongly coincide at terrestrial wavelengths when $D_e < \sim 60 \mu\text{m}$, which is where this D_e -CWC assumption appears poorest. Treating optical properties solely in terms of D_e and IWC may lead to errors up to 24%, 26% and 20% for terrestrial radiation in the window region regarding the absorption and extinction coefficients and the single scattering albedo, respectively. Outside the window region, errors may reach 33% and 42% regarding absorption and extinction. The magnitude and sign of these errors can change rapidly with wavelength, which may produce significant errors in climate modeling, remote sensing and other applications concerned with the wavelength dependence of radiation.

Where the D_e -CWC assumption breaks down, ice cloud optical properties appear to depend on D_e , IWC and the PSD shape. Optical property parameterizations in climate models and remote sensing algorithms based on historical PSD measurements may exhibit errors due to previously unknown PSD errors (i.e. the presence of ice artifacts due to the shattering of larger ice particles on the probe inlet tube during sampling). More recently developed cloud probes are designed to mitigate this shattering problem. Using realistic PSD shapes for a given temperature (and/or IWC) and cloud type may minimize errors associated with PSD shape in ice optics parameterizations and remote sensing algorithms.

While this topic was investigated using two ice optics schemes (the Yang et al., 2005 database and the modified anomalous diffraction approximation, or MADA), a physical understanding of the limitations of the D_e -IWC assumption was made possible by using MADA. MADA allows one to approximate the contribution of photon tunneling to absorption relative to other optical processes, which reveals that part of the error regarding the D_e -IWC assumption can be associated with tunneling. By relating the remaining error to the radiation penetration depth in bulk ice (ΔL) due to absorption, the domain where the D_e -IWC assumption is weakest was described in terms of D_e and ΔL .

Citation: D.L. Mitchell, R. P. Lawson, and B. Baker (2011), Understanding effective diameter and its application to terrestrial radiation in ice clouds, Atmos. Chem. Phys., 11, 3417-3429, doi:10.5194/acp-11-3417-2011.

Indirect and Semi-Direct Aerosol Campaign

G.M. McFarquhar, S. Ghan, J. Verlinde, A. Korolev, J.W. Strapp, B. Schmid, J.M. Tomlinson, M. Wolde, S.D. Brooks, D. Cziczo, M.K. Dubey, J. Fan, C. Flynn, I. Gultepe, J. Hubbe, M.K. Gilles, A. Laskin, R.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

Abstract

A comprehensive dataset of microphysical and radiative properties of aerosols and clouds in the boundary layer in the vicinity of Barrow, Alaska, was collected in April 2008 during the Indirect and Semi-Direct Aerosol Campaign (ISDAC). ISDAC's primary aim was to examine the effects of aerosols, including those generated by Asian wildfires, on clouds that contain both liquid and ice. ISDAC utilized the Atmospheric Radiation Measurement Program's permanent observational facilities at Barrow and specially deployed instruments measuring aerosol, ice fog, precipitation, and radiation. The National Research Council of Canada Convair-580 flew 27 sorties and collected data using an unprecedented 41 state-of-the-art cloud and aerosol instruments for more than 100 h on 12 different days. Aerosol compositions, including fresh and processed sea salt, biomass burning particles, organics, and sulfates mixed with organics, varied between flights. Observations in a dense arctic haze on 19 April and above, within, and below the single-layer stratocumulus on 8 and 26 April are enabling a process-oriented understanding of how aerosols affect arctic clouds. Inhomogeneities in reflectivity, a close coupling of upward and downward Doppler motion, and a nearly constant ice profile in the single-layer stratocumulus suggests that vertical mixing is responsible for its longevity observed during ISDAC. Data acquired in cirrus on flights between Barrow and Fairbanks, Alaska, are improving the understanding of the performance of cloud probes in ice. Ultimately, ISDAC data will improve the representation of cloud and aerosol processes in models covering a variety of spatial and temporal scales, and determine the extent to which surface measurements can provide retrievals of aerosols, clouds, precipitation, and radiative heating.

Citation: G.M. McFarquhar, S. Ghan, J. Verlinde, A. Korolev, J.W. Strapp, B. Schmid, J.M. Tomlinson, M. Wolde, S.D. Brooks, D. Cziczo, M.K. Dubey, J. Fan, C. Flynn, I. Gultepe, J. Hubbe, M.K. Gilles, A. Laskin, R.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, Indirect and semi-direct aerosol campaign: The impact of Arctic aerosols on clouds, *Bull. Amer. Meteor. Soc.*, 183--201, doi:10.1175/2010BAMS2935.1.

The dependence of ice microphysics on aerosol concentration in Arctic mixed-phase stratus clouds during ISDAC and M-PACE

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Abstract

Cloud and aerosol data acquired by the National Research Council of Canada (NRC) Convair-580 aircraft in, above, and below single-layer arctic stratocumulus cloud during the Indirect and Semi-Direct Aerosol Campaign (ISDAC) in April 2008 were used to test three aerosol indirect effects hypothesized to act in mixed-phase clouds: the riming indirect effect, the glaciation indirect effect, and the thermodynamic indirect effect. The data showed a correlation of $R = 0.78$ between liquid drop number concentration, N_{liq} inside cloud and ambient aerosol number concentration N_{PCASP} below cloud. This, combined with increasing liquid water content LWC with height above cloud base and the nearly constant vertical profile of N_{liq} , suggested that liquid drops nucleated from aerosol at cloud base. No evidence of a riming indirect effect was observed, but a strong correlation of $R = 0.69$ between ice crystal number concentration N_i and N_{PCASP} above cloud was noted. Increases in ice nuclei (IN) concentration with N_{PCASP} above cloud for 2 flight dates combined with the subadiabatic LWC profiles suggest possible mixing of IN from cloud top consistent with the glaciation indirect effect. The lower N_{ice} and lower effective radius r_{el} for the more polluted ISDAC cases compared to data collected in cleaner single-layer stratocumulus conditions during the Mixed-Phase Arctic Cloud Experiment is consistent with the operation of the thermodynamic indirect effect. However, more data in a wider variety of meteorological and surface conditions, with greater variations in aerosol forcing, are required to identify the dominant aerosol forcing mechanisms in mixed-phase arctic clouds.

Citation: Jackson, R. C., G. M. McFarquhar, A. V. Korolev, M. E. Earle, P. S. K. Liu, R. P. Lawson, S. Brooks, M. Wolde, A. Laskin, and M. Freer (2012), The dependence of ice microphysics on aerosol concentration in arctic mixed-phase stratus clouds during ISDAC and M-PACE, *J. Geophys. Res.*, 117, D15207, doi:10.1029/2012JD017668.

Appendix B: Poster Presentations

Poster presented at the 2012 ASR Science Team meeting in Arlington, VA

Appendix C: draft of Lance et al. (2013)

for submission to the journal Atmospheric Chemistry and Physics

Modeling Optical Properties and Radiative Effects of Stratiform Arctic Mixed-Phase Clouds using Comprehensive In-Situ Cloud Microphysical Measurements from ISDAC 2008

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Abstract. In this study, in-situ measurements from the 2008 Indirect and Semi-Direct Aerosol Campaign (ISDAC) of individual ice particles and water droplets from multiple independent cloud particle probes have been combined to infer separate ice and water particle size distributions for stratiform Arctic mixed-phase clouds. Shortwave and longwave optical properties (extinction, single scatter albedo and asymmetry parameter) are then calculated using a new version of the modified anomalous diffraction approximation (MADA) code, which has been altered to account for both the liquid and ice phases. A two-stream radiative transfer model is then used to compute vertical profiles of radiative forcing and heating rates.

1 Introduction

Low altitude stratiform clouds are an important component of the Arctic climate system. These clouds are often mixed-phase, with supercooled liquid water layer(s) embedded within precipitating ice (Pinto, 1998; Lawson et al., 2001; Shupe, 2011; de Boer et al., 2011).

The radiative effect of Arctic mixed-phase clouds depends on their optical thickness (or optical depth), which is controlled in part both by the physical thickness of the cloud and the cloud microphysical properties, such as liquid water content (LWC) and ice water content (IWC). In the Arctic, optically thick clouds can have a greater affect on longwave heating rates than on solar irradiance, due in part to low solar angle and high albedo of snow and ice covered surfaces, which means that (in contrast to temperate latitudes) optically thick clouds in the lower atmosphere result in net warming of the Arctic surface for much of the year (Intrieri et al., 2002).

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2 Methods

2.1 ISDAC 2008

The Indirect and Semi-Direct Aerosol Campaign (ISDAC) took place in the vicinity of Barrow, AK in April 2008 (McFarquhar et al., 2011).

The case studies analyzed in the present study took place during two flights described in further detail by Jackson et al. (2012), referred to as April 18f2 and April 26f2 (or Research Flights RF23 and RF31, respectively). Note that reference to April 18f1 in Jackson et al. (2012) were made in error, and should have been referenced as April 18f2, which is the same flight discussed here. Jackson et al. (2012) identified RF23 as a flight for which aerosol pollution had an affect on the cloud microphysics, particularly the cloud droplet number concentration and cloud droplet effective radius. Clouds measured during RF31 were also described by Earle et al. (2011) and McFarquhar et al. (2011).

In the current study, measurements from RF23 and RF31 are used to evaluate the affect of cloud microphysical properties on shortwave cooling and longwave heating rates. Repeated cloud vertical profiles were obtained on both flights, which allowed for robust characterization of the above-cloud temperature inversion as well as the microphysical properties of the mixed-phase stratus deck and ice precipitation.

Observations reported in this paper were taken onboard the NRC Convair-580 aircraft (CV-580). Table 1 lists the cloud particle probe measurements used in the current study.

2.2 In-Situ Cloud Measurements

Measured number, area and mass distributions from the CDP, 2D-S and 2D-P are combined to obtain separate water droplet and ice particle size distributions. The CPI images are used to evaluate the shape of the ice particles at much higher image resolution. Each cloud probe instrument is subject to

Table 1. Cloud probe instruments operating during ISDAC 2008, from which the ice and water particle size distributions for the current study are derived.

Instrument	Manufacturer	Nominal Size Range (μm)	Size Resolution (μm / pixel)
CPI v.2	SPEC, Inc.	10–2,000	2.3
CDP	DMT, Inc.	2–50	N/A
2D-S	SPEC, Inc.	10–3,000	10
2D-P	PMS, Inc.	100–13,000	100

different limitations, which depend on the size, shape and concentration of particles being observed. The observations are therefore combined in slightly different ways in different cloud situations. Figure 1 shows the CDP, 2D-S and 2D-P number, area and mass distributions averaged over a 2.3 minute period on RF31. For clarity, the smallest 2 size bins for the 2D-S and the smallest 4 size bins for the 2D-P are not shown. Together, the observations span the size range from $2\text{ }\mu\text{m}$ to 1 cm , corresponding to nearly 4 orders of magnitude in particle size and nearly 11 orders of magnitude in number concentration.

For the mixed-phase clouds in this study, the CDP observations are assumed to represent liquid droplets, and are used to characterize the size distribution of particles with diameter $< 50\text{ }\mu\text{m}$. However, there are times when the droplet concentration in this size range is below the counting limit of the CDP sample volume, and during those times the 2D-S observations are used instead. Since the droplet concentrations measured by the CDP are typically $< 200\text{ cm}^{-3}$ for both RF31 and RF23 (McFarquhar et al., 2011), undercounting errors due to coincidence in the CDP are assumed to be negligible (Lance et al., 2010; Lance, 2012).

The 2D-S observations are corrected for ice shatter artifacts using an algorithm based on particle interarrival times (Lawson, 2011). In addition, an algorithm to distinguish round particles from non-round particles was implemented for analysis of the 2D-S data, to estimate the concentration of ice particles and liquid water drops with $> 100\text{ }\mu\text{m}$ diameter (Montero and Bribeasa, 2009). Note, however, that there are seldom liquid drops with diameter $> 100\text{ }\mu\text{m}$ in the clouds analyzed here. CPI images are used to verify whether particles measured by the 2D-S with diameter $< 100\text{ }\mu\text{m}$ are spherical or not.

To estimate mass distributions from individual 2D-S particle images, a mass parameterization based on the combined single parameter (CSP) is used (Eq. 1-2). The CSP , as defined by Baker and Lawson (2006), incorporates the maximum length (L) and perpendicular width (W) dimensions of each particle as well as the particle outer perimeter (P) and projected area (A , or the number of shaded pixels). This is the first time the IWC parameterization based on the CSP

Fig. 1. Combining measurements from multiple in-situ cloud probes to determine liquid (solid lines) and ice (dotted lines) particle size distributions. CDP observations are colored in blue, 2D-S observations are colored in black and observations are colored in red. 2D-P measurements are used for particles with maximum dimension $> 1.1\text{ mm}$.

has been applied to 2D-S data.

$$CSP = AW(2L + 2W)/P \quad (1)$$

$$\text{mass}[\text{mg}] = 0.135(CSP[\text{mm}^3])^{0.793} \quad (2)$$

To derive mass distributions from 2D-P observations, a mass parameterization based on particle projected area is used. The Baker and Lawson (2006) parameterization is used for the 2D-S dataset is applied to individual particle images. However, for the 2D-P measurements, an approximation is applied based on the number distribution ($N(D, AR)$) binned as a function of particle diameter (D) and area ratio (AR), as defined by McFarquhar and Heymsfield (1996). The 2D-P dataset was binned with 10 area ratio bins and 64 size bins. For a given particle size bin and area ratio bin, the particle

area is approximated as $A_m = (\pi/4)D_m^2 AR_m$, where D_m is the midpoint of the size bin and AR_m is the midpoint of the area ratio bin. To derive the 2D-P area distribution ($A(D)$), such as shown in Fig. 1b, A_m is multiplied by the number concentration of particles and summed over all area ratio bins according to Eq. 4. The 2D-P mass distribution ($M(D)$) is then derived according to Eq. 5, with multiplier and exponent from Baker and Lawson (2006).

$$N(D) = \sum_{AR} N(D, AR) \quad (3)$$

$$A(D) = \sum_{AR} N(D, AR) A_m \quad (4)$$

$$M(D) = \sum_{AR} N(D, AR) (0.115 A_m^{1.218}) \quad (5)$$

where $M(D)$ has units of $[mg L^{-1} \mu m^{-1}]$, $N(D, AR)$ has units of $[No. L^{-1} \mu m^{-1}]$ and A_m has units of $[mm^2]$.

To avoid uncertainties involved with images that overflow the field of view (FOV) of the 2D-S diode array and are therefore only partially observed, the 2D-P measurements are used whenever the particle maximum dimension approaches the FOV of the 2D-S diode array (i.e. 1.3 mm). The size cutoff between 2D-S and 2D-P measurements used depends upon the ambient particle number distribution. The 2D-P has a larger sample volume for particles ~ 1 mm but lower size resolution than the 2D-S, and these tradeoffs are considered on a case by case basis. For the example shown in Fig. 1, a size cutoff of 1.1 mm is used, yielding continuous distributions for the size transition between 2D-S and 2D-P measurements. Note that although the 2D-S and 2D-P mass distributions were calculated using different parameterizations, the mass distributions agree nearly as well as the 2D-S and 2D-P area and number distributions.

2.3 Calculation of Cloud Optical Properties

The Modified Anomalous Diffraction Approximation (MADA) code (Mitchell et al., 2006) has been used in previous studies to calculate the optical properties of cirrus clouds (e.g. (Mitchell et al., 2006; Lawson et al., 2010)) and liquid phase clouds (Mitchell, 2000): single scatter albedo (w_0) and volume extinction coefficient (B_{ext}). In the current study, the MADA code is modified for universal application to ice, liquid and mixed phase clouds. A key advance is that the MADA treatment of ice phase optical properties does not require assumptions of idealized particle shapes, but rather calculates optical properties directly from measurements of the ice particle number, area and mass. Errors are reasonably well quantified, as described by Mitchell et al. (2006).

Measured particle size distributions (PSD) are used as inputs to the MADA code. Each size bin has a number, projected area and mass concentration, and a separate file is read

for each property. The ratio of the total volume (V) to projected area (A) in each bin gives effective photon path for that bin (where volume = mass/bulk density). The V/P ratio is used by MADA to calculate optical properties. Two tunneling efficiencies are applied; one for the small particle size mode and one for the large particle size mode (0.8 and 0.3, respectively, based on Table 1 in Mitchell et al. (2006)).

The total extinction and absorption coefficients, B_{ext} and B_{abs} , are calculated by adding the corresponding coefficients for liquid water and ice:

$$B_{ext} = B_{ext}(ice) + B_{ext}(liq) \quad (6)$$

$$B_{abs} = B_{abs}(ice) + B_{abs}(liq) \quad (7)$$

Then $w_0 = 1 - (B_{abs}/B_{ext})$, for each wavelength. Cloud effective radius (R_{eff}) is calculated based on the condensed water content (CWC), bulk particle density (ρ) and projected area of individual particle images (Mitchell, 2002; Mitchell et al., 2011). Equation 8 can be used for liquid, ice or mixed-phase clouds.

$$R_{eff} = (3/2)CWC/\rho P \quad (8)$$

For wavelengths $< 3 \mu m$, asymmetry parameter (g) for ice particles is derived based on the Fu (2007) parameterizations for hexagonal columns and plates. As Fu (2007) and other studies have shown, g is primarily a function of the aspect ratio and surface roughness of a pristine ice crystal or a representative component element in a complex ice crystal or aggregate. This principle enables us to generalize the Fu (2007) scheme to address complex crystal shapes and aggregates using a prescribed ice particle habit recipe based on 2D-S and CPI images. For example, dendrites are parameterized by calculating g for a representative plate-like component on a dendrite branch, using the plate scheme of Fu (2007) with aspect ratios based on Auer and Veal (1970). The effective asymmetry parameter is then calculated weighted by the fraction of particles with a given habit. When absorption is significant, g is also a function of w_0 in the Fu scheme. Since w_0 is predicted by MADA, in this way the Fu scheme is seamlessly integrated into the MADA framework, predicting g in terms of the observed ice particle shape recipe and measurements of ice particle number, area and mass. Several studies show ice particles have rough ice surfaces (e.g. Macke et al (1996); Fu (2007); van Didenhoven (2012)), and g is calculated for rough surfaces as described by Fu (2007). For wavelengths $> 3 \mu m$, the asymmetry parameter for ice particles is derived from the scheme of (Yang et al., 2005). Asymmetry parameter for liquid drops is implemented in the current version of the MADA code using the parameterizations of Slingo (1989) for shortwave radiation bands and Savijarvi and Raisanen (1988) for the longwave radiation bands.

2.4 Radiative Transfer Model

The optical properties output by the new mixed-phase MADA code were optimized for input to a 2-stream (i.e. upward and downward propagating) radiative transfer model developed by Toon et al. (1989)) with 44 wavelength bands from 250 nm to 40 μm . The Toon et al. (1989) model has been used previously to determine heating rates as a function of altitude in cirrus clouds (Lawson et al., 2010). The same approach is used here to determine vertical heating rate profiles above, within and below the mixed-phase cloud deck of the stratiform Arctic clouds described in this paper.

3 Results

3.1 Cloud Microphysics Measurements (RF31)

For the 27 April flight (RF31), in-situ cloud measurements are analyzed over a 13 minute time period during which the CV-580 made ten vertical profiles through a mixed-phase stratus deck (00:57:45–01:11:11). The ice particles measured within and below the mixed-phase cloud deck were often $> 1 \text{ mm}$ and typically with dendritic or stellar structure. Figure 2 shows representative 2D-S images from RF31 in a mixed-phase cloud region where both cloud droplets and ice particles were observed (Fig. 2a) and below the mixed-phase cloud region where only large ice particles were observed (Fig. 2b). Cloud particle size distributions obtained from CDP, 2D-S, and 2D-P measurements are shown in the top panel of Fig. 2c as a function of time, with color representing the number concentration of particles normalized by the size bin width to allow direct comparison between different instruments, where red indicates the highest number concentrations observed and blue indicates the lowest number concentrations observed. The same color scale is used to indicate the same dynamic range in number concentrations for all three instruments (i.e. 10^{-6} – $10^5 \text{ L}^{-1} \mu\text{m}^{-1}$). White space in the size distributions result from ambient concentrations that are lower than the ability of the instrument to detect at 1 second time resolution. Ambient pressure altitude (black line) and temperature (red line) are shown in the bottom panel of Fig. 2c, and droplet concentrations integrated from the CDP size distributions are also shown (blue line).

The CDP size distributions show an increase in cloud droplet size with altitude, with an abrupt decrease in droplet concentrations as the CV-580 ascended above-cloud, as indicated with vertical lines drawn in Fig. 2c at times when the CV-580 penetrated the temperature inversion at cloud-top. Droplet concentrations also decreased abruptly as the CV-580 descended below cloud-base. Notice, however, that the large particles ($> 100 \mu\text{m}$) measured by the 2D-P and the 2D-S continued to be detected below cloud-base, even at the lowest altitude for which measurements were obtained ($\sim 400 \text{ m asl}$).

Fig. 2. Cloud microphysical observations from the 27 April flight (RF31). 2D-S images are shown representing observations a) within the mixed-phase cloud deck and b) below the mixed-phase cloud deck. c) 2D-P, 2D-S and CDP size distributions and CDP droplet concentrations (cm^{-3}) are shown as a function of time, along with ambient temperature and pressure altitude. Vertical lines are drawn to aid in visualizing time periods above-cloud.

The change in cloud microphysical properties with altitude is explored further by averaging water droplet and ice particle size distributions over 4 vertical regions of cloud. As indicated by the sloping temperature trend in Fig. 2c, the cloud deck was not horizontally homogeneous. To account for the sloping cloud field, time periods with similar cloud microphysics and similar altitude relative to cloud-top were identified, to obtain the 4 vertical regions for which average water and ice particle size distributions could be obtained (Fig. 3).

Figure 4 shows the average pressure altitude, temperature, IWC, LWC, drop concentration (N_d), ice concentration (N_i) and effective radius (R_{eff}) corresponding to each of the 4 cloud regions and therefore each of the water and ice size distributions shown in Fig. 3. The average altitude of cloud-top for the case study on RF31 is 830 m, and the average altitude of cloud-base (defined here as the region with > 10

Fig. 3. Liquid water and ice particle distributions averaged over 4 vertical cloud regions on the 27 April 2008 flight (RF31). Water droplets and ice particles photographed by the CPI are shown at the right.

Fig. 4. Average temperature and microphysical properties for the 4 vertical regions identified for the mixed-phase cloud on RF31. Average cloud-top and cloud-base are indicated with blue horizontal dashed lines. The lowest altitude where ice precipitation was observed is indicated with the black horizontal dashed line, which also corresponds to the lowest flight altitude attained.

cm^{-3} droplet concentrations) is 678 m, corresponding to an average thickness for the mixed-phase cloud deck of 152 m. However, ice precipitation particles were observed at altitudes as low as 400 m (the lowest flight altitude attained). The highest average LWC (0.125 g m^{-3}) was found near cloud-top (Region 4), while the highest average IWC (0.048 g m^{-3}) was found below the mixed-phase cloud deck (Region 1).

The CPI images observed during RF31 confirm that the predominant ice particle habit is dendritic (both within and below the mixed-phase cloud deck) but also show a small number of stellar and hexagonal plates at sizes $< 400 \mu\text{m}$ (Fig. 3). Due to their abundance, most of the droplets detected by the CPI during RF31 were in the size range $10\text{--}20 \mu\text{m}$ diameter. Drops with diameters as large as $53 \mu\text{m}$ are observed by the CPI during this flight, but only when the concentration of smaller droplets decreases, since the CPI detects only a small subset of all particles (a maximum of ~ 70 particles per second for this version of the CPI). Figure 5a shows a time period when the droplets detected by the CPI have $> 30 \mu\text{m}$ average diameter for more than 2 seconds, as a result of a substantial decrease in the concentration of droplets $10\text{--}30 \mu\text{m}$ (Note that this time period is not included in the average particle size distributions shown in Fig. 3, since the cloud microphysics for this cloud pass were substantially different from the other cloud passes in Fig. 2c). This example demonstrates that large supercooled drops can exist in these types of clouds, and further emphasizes that the CPI images can be used to identify the phase of particles $30\text{--}100 \mu\text{m}$, but only when particles in this size range have significant relative abundance.

Fig. 5. CPI images showing: a) some of the largest drops detected on RF31 (at 01:12:02.263–01:12:04.960), and b) small ice particles detected below the mixed-phase cloud layer (at 01:10:10.445–01:10:21.813).

There is no clear evidence of natural ice particles smaller than $\sim 80 \mu\text{m}$ for this flight. There is a very small subset of particles in the $10\text{--}20 \mu\text{m}$ size range that are clearly non-spherical (such as those shown in Fig. 5b), and these particles are good candidates for ice particles, but they can only be observed when the concentration of droplets is very low (e.g. $<$

1 cm⁻³, as below the mixed-phase cloud deck) due to their infrequent occurrence. We cannot rule out the possibility that any rare small ice particles observed by the CPI could have resulted from shattering of larger ice particles, since we know that the presence of particles > 1 mm can lead to ice particle shattering, especially with tubular inlets (McFarquhar et al., 2011; Lawson, 2011), and since ice particles < ~80 μm that are observed by the CPI do not have obvious ice crystal symmetry (Fig. 5b), which could rule out shattering. Note that shattering of ice particles upon impact with the leading edges of the CPI does not help to identify ice shattering on the other cloud probe instruments, since the CPI has a very different external geometry than the CDP, 2D-S or 2D-P.

3.2 Cloud Microphysics Measurements (RF23)

For the 18 April flight (RF23), in-situ cloud measurements are analyzed over a 12 minute time period during which the CV-580 made eight vertical profiles through a mixed-phase stratus deck (22:46:32–22:58:34). The ice particles measured within and below the mixed-phase cloud deck were generally < 1 mm and typically with irregular structure. Figure 6 shows representative 2D-S images from RF23 in a mixed-phase cloud region where both cloud droplets and ice particles were observed (Fig. 6a) and below the mixed-phase cloud region where only ice particles were observed (Fig. 6b). Note the two in-focus 2D-S images that are round in the top panel of Fig. 6b, which are probably large drops, with diameters of 141 and 249 μm, respectively. Cloud particle size distributions obtained from CDP, 2D-S, and 2D-P measurements are shown in Fig. 6c as a function of time.

The altitude of the mixed-phase cloud sampled on RF23 was much higher than the mixed-phase cloud sampled on RF31 (3780m and 790m average cloud-top altitude, respectively), but the thickness of the mixed-phase cloud region was roughly the same in both cases (152 m and 164 m for RF31 and RF23, respectively). Consistent with the higher altitude, cloud top temperature for RF23 is 6°C colder on average than cloud-top temperature for RF31. The mixed-phase clouds measured during RF23 and RF31 both showed a strong temperature inversion above cloud-top.

Four vertical cloud regions were identified for RF23 based on cloud microphysical properties and proximity to cloud-top. The average liquid drop and ice particle size distributions for these four altitude regions are shown in Fig. 8, with the corresponding average vertical profile of bulk microphysical properties (IWC, LWC, N_d, N_i and R_{eff}) and temperature shown in Fig. 7. The highest average LWC (Region 4 near cloud-top) was on average 0.08 g m⁻³, and IWC was on average < 0.0025 g m⁻³ for all vertical cloud regions.

The CPI images confirm that ice particles were dominated by irregular shapes, but the high image resolution of the CPI images also indicates the presence of plate-like appendages, which could affect the optical properties of the particles, especially the asymmetry parameter. The CPI images also in-

Fig. 6. Cloud microphysical observations from the 18 April flight (RF23). All else is the same as in Fig. 2.

Fig. 7. Average temperature and microphysical properties for the 4 vertical regions identified for the mixed-phase cloud on RF23. Average cloud-top and cloud-base are indicated with blue horizontal dashed lines. The lowest altitude where ice precipitation was observed is indicated with the black horizontal dashed line, which also corresponds to the lowest flight altitude attained.

Fig. 8. Liquid water and ice particle distributions for the 4 Regions on the 18 April 2008 flight (RF23). Water droplets and ice particles photographed by the CPI are shown at the right.

Fig. 9. Computed optical properties using the new mixed-phase MADA code, for the four vertical Regions summarized in Fig. 3 and Fig. 8 for RF31 and RF23, respectively.

dicates that the cloud droplets and ice particles detected on RF23 were typically smaller than those detected on RF31, consistent with the CDP, 2D-S and 2D-P size distributions (Fig. 6c).

3.3 Computed Optical Properties

Figure 9 shows the wavelength dependent extinction coefficient, single scatter albedo and asymmetry parameter computed for the 4 vertical cloud regions of RF31 and RF23, using the liquid and ice size distributions shown in Fig. 3 and 8, respectively. The largest difference in asymmetry parameter and single scatter albedo occurs in the longwave for the lowest altitude (Region1) below the mixed-phase cloud deck on RF31. The extinction coefficient is greater for RF31 than for RF23, at every vertical region within and below the mixed-phase cloud deck.

3.4 Vertical Profiles of Heating/Cooling Rates

4 Conclusions

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