Ubiquitous low-level liquid-containing Arctic clouds: New observations and climate model constraints from CALIPSO-GOCCP

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Ubiquitous low-level liquid-containing Arctic clouds: New observations and climate model constraints from CALIPSO-GOCCP

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[1] Ground-based observations show that persistent liquid-containing Arctic clouds occur frequently and have a dominant influence on Arctic surface radiative fluxes. Yet, without a hemispheric multi-year perspective, the climate relevance of these intriguing Arctic cloud observations was previously unknown. In this study, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) observations are used to document cloud phase over the Arctic basin (60–82°N) during a five-year period (2006–2011). Over Arctic ocean-covered areas, low-level liquid-containing clouds are prevalent in all seasons, especially in Fall. These new CALIPSO observations provide a unique and climate-relevant constraint on Arctic cloud processes. Evaluation of one climate model using a lidar simulator suggests a lack of liquid-containing Arctic clouds contributes to a lack of "radiatively opaque" states. The surface radiation biases found in this one model are found in multiple models, highlighting the need for improved modeling of Arctic cloud phase. **Citation:** Cesana, G., J. E. Kay, H. Chepfer, J. M. English, and G. de Boer (2012), Ubiquitous low-level liquid-containing Arctic clouds: New observations and climate model constraints from CALIPSO-GOCCP, *Geophys. Res. Lett.*, *39*, L20804, doi:10.1029/2012GL053385.

1. Introduction

[2] Low-level clouds frequently occur in the Arctic and exert a large influence on Arctic surface radiative fluxes [e.g., *Shupe and Intrieri*, 2004; *Shupe*, 2011; *de Boer et al.*, 2009; *Morrison et al.*, 2012] and Arctic climate feedbacks [e.g., *Winton*, 2006; *Kay and Gettelman*, 2009; *Kay et al.*, 2012a]. Ground-based remote sensing observations taken during the 1997–1998 Surface Heat Budget of the Arctic (SHEBA) [*Uttal et al.*, 2002] experiment first showed the dominant influence of liquid-containing Arctic clouds on surface radiative fluxes in all seasons [*Persson et al.*, 2002; *Shupe and Intrieri*, 2004]. During the SHEBA winter, surface net longwave radiation ($F_{LW,NET}$) had a bi-modal distribution, with peaks that have subsequently been termed "radiatively clear" and "radiatively opaque" states [e.g., *Morrison et al.*, 2012, Figure 4; *Stramler et al.*, 2011]. Cloud phase helps explain these two distinct radiative states. Arctic ice clouds tend to have small optical depths and a weak influence on $F_{LW,NET}$, and thus can be present even in a "radiatively clear" state. In contrast, Arctic liquid-containing clouds generally have large optical depths and a dominant influence on $F_{LW,NET}$ [*Shupe and Intrieri*, 2004], and therefore help explain the "radiatively opaque" state [*Doyle et al.*, 2011].

[3] Available observations and theory suggest liquid water is present in Arctic clouds year-round due to interactions between local microphysical and large-scale synoptic meteorological processes [*Doyle et al.*, 2011; *Morrison et al.*, 2012; *Stramler et al.*, 2011]. Local microphysical processes such as the Wegener-Bergeron-Findeisen (WBF) process [*Wegener*, 1911; *Bergeron*, 1935; *Findeisen*, 1938] and heterogeneous ice nucleation rates have a large influence on the phase partitioning in Arctic clouds and thus the radiatively important liquid-containing cloud amount. In addition, large-scale atmospheric patterns play a key role in setting atmospheric temperature, moisture, and aerosol content and thus strongly affect cloud properties and $F_{LW,NET}$ [*Morrison et al.*, 2012]. There is no doubt that the ubiquitous presence of the liquid phase at temperatures significantly below 0°C is important for Arctic radiative fluxes, and therefore Arctic climate. Yet while individual field campaigns [e.g., *Shupe et al.*, 2006; *Prenni et al.*, 2007] and land-based observatories (e.g. North Slope of Alaska, Eureka, Summit, Ny Alesund) have demonstrated the frequent presence of supercooled liquid-containing low-level Arctic clouds, a hemispheric multi-year perspective on the climatic importance of these clouds has been lacking.

[4] In this paper, a new observational technique (G. Cesana and H. Chepfer, Evaluation of the cloud water phase in a climate model using CALIPSO-GOCCP, submitted to *Journal of Geophysical Research*, 2012), based on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) spaceborne lidar observations [*Winker et al.*, 2009], is used to document geographic, seasonal, and vertical variations in Arctic cloud phase. This unique hemispheric Arctic cloud phase climatology is then used to evaluate the influence of Arctic cloud phase on Arctic cloud radiative flux biases in climate models. The presented findings suggest that Arctic cloud phase is a useful parameter for climate model evaluation and an important target for climate model improvement.

2. Methods

[5] The GCM Oriented CALIPSO Cloud Product (CALIPSO-GOCCP) [*Chepfer et al.*, 2010] cloud phase detection retrieval algorithm and related simulator improvements used in this study are described by Cesana and Chepfer

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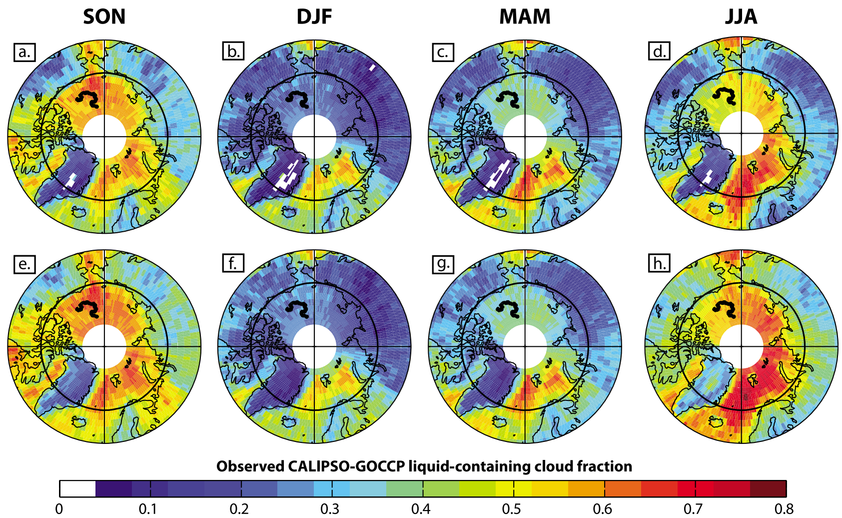

Figure 1. Arctic maps of the seasonal variations in liquid-containing cloud fraction in CALIPSO-GOCCP observations for the period 2006–2011: (a) SON low-level (0–3.36 km above sea level) cloud (b) DJF low-level cloud (c) MAM low-level cloud and (d) JJA low-level cloud. (e–h) As in Figures 1a–1d but for liquid-containing clouds at all levels. Liquid cloud fractions based on both daytime and night-time CALIPSO-GOCCP observations.

(submitted manuscript, 2012), and therefore only a brief description is provided here. CALIPSO-GOCCP has been developed from Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) level 1 products [*Winker et al.*, 2009] in order to evaluate clouds in climate models. CALIPSO-GOCCP cloud detection (scattering ratio (SR) > 5) occurs every 333 m along the satellite track using lidar profiles with a vertical resolution of 480 m. Next, cloudy pixels are classified as liquid-containing, ice-dominated or undefined using the polarization state of laser light scattered by cloud particles (multiple scattering is taken into account) and temperature. Finally, the retrievals are averaged over a 2° × 2° grid to produce monthly, global, three-dimensional cloud fraction. While a temperature threshold is a part of the phase retrieval, it has a minor influence on Arctic cloud phase retrievals. Between 60° and 82°N, the temperature criterion is used to identify the phase of less than 1.3% of the identified cloudy cases.

[6] CALIPSO-GOCCP observations are affected by spatio-temporal sampling, lidar attenuation, and retrieval assumptions. A lidar simulator can emulate these three idiosyncrasies associated with observing clouds using a spaceborne lidar, and thus a lidar simulator is an essential tool for robust evaluation of model-simulated clouds using lidar observations. In this study, we use the ensemble "GCM + CALIPSO lidar simulator" [*Chepfer et al.*, 2008], which has been developed to be consistent with CALIPSO-GOCCP observations. Briefly, this lidar simulator includes three modules: a subgridding module [*Klein and Jakob*, 1999], an attenuation module [*Chepfer et al.*, 2008], and a phase diagnosis module that implements the same retrieval on model lidar backscatter profiles as was implemented on observed lidar backscatter profiles (Cesana and Chepfer, submitted manuscript, 2012).

3. Observed Geographic, Seasonal, and Vertical Distributions of Arctic Cloud Phase

[7] Figure 1 shows the seasonal geographic distributions of low-level liquid-containing Arctic clouds (top row) and liquid-containing Arctic clouds at all levels (bottom row). Liquid-containing clouds are present over the Arctic Ocean and North Atlantic in all seasons. These liquid-containing Arctic clouds exist in an environment with temperatures that are frequently well below 0°C during Fall (SON), Winter (DJF), and Spring (MAM). The largest liquid-containing cloud fractions occur during SON, which is also the season with the most Arctic clouds detected by CALIPSO-GOCCP [e.g., *Kay et al.*, 2012b, Figure 11]. Even during DJF, the season with the least supercooled liquid-containing Arctic clouds, liquid-containing Arctic cloud fractions exceed 0.2 over the entire ocean-covered Arctic domain. DJF and MAM have relatively large liquid-containing cloud fractions (>0.5) associated with the semi-permanent Aleutian and Icelandic Lows, and relatively small liquid-containing cloud fractions over the central Arctic Ocean (0.2–0.4). The contrast between the semi-permanent lows and the central Arctic Ocean is reduced during Summer (JJA) and Fall (SON) when large liquid-containing cloud fractions (>0.5) are present over all high northern latitude ocean areas.

[8] Figures 2a–2d show observed monthly vertical distribution of CALIPSO-GOCCP liquid-containing and ice-dominated clouds averaged over the high northern latitude ocean-covered areas (70–82°N). The CALIPSO-GOCCP cloud fraction data are shown with both height (Figures 2a and 2b) and temperature (Figures 2c and 2d) as the vertical coordinate. As discussed by Cesana and Chepfer (submitted manuscript, 2012), the temperature ranges for detected ice-dominated and liquid-containing clouds are consistent with physical theory: liquid is only present above the homogeneous freezing temperature (∼−42°C) and ice is only present below the melting temperature (0°C).

[9] Over the high northern latitude oceans, most liquid-containing clouds occur below 3 km and at temperatures between −25 and 0°C (Figures 2a and 2c), a result that is similar to available ground-based observations [e.g., *de Boer et al.*, 2011; *Shupe*, 2011, Figure 3]. Moreover, a subset of CALIPSO-GOCCP measurements above Barrow, Alaska, Eureka, Nunavut and the SHEBA ship track (not shown) produces phase results that are similar to ground-based

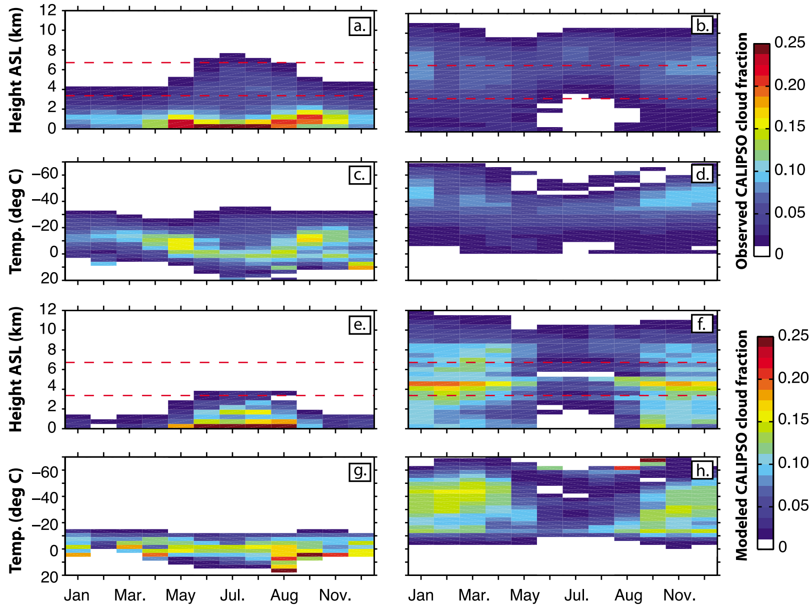

Figure 2. Monthly vertical profiles of cloud fraction averaged over the Arctic Ocean (70–82 N, ocean-only) for the period 2006–2011: (a) Observed liquid-containing clouds as a function of height (km) and month of the year from CALIPSO-GOCCP. (b) Same as Figure 2a but for ice-dominated clouds. (c) Observed liquid-containing clouds as a function of temperature (°C) and month of the year from CALIPSO GOCCP. (d) Same as Figure 2c but for ice-dominated clouds. (e–h) same as Figures 2a–2d but for a climate model (LMDZ5B) [*Hourdin et al.*, 2012] using the CALIPSO lidar simulator. Temperatures are from GMAO reanalysis [*Bey et al.*, 2001] provided with the CALIPSO level 1 data. Red dashed lines discriminate between low- and mid-level clouds (3.36 km) and mid- and high-level clouds (6.72 km).

retrievals in *Shupe* [2011, Figure 3]. The presence of supercooled liquid over such a large temperature range illustrates that temperature is only one of many factors controlling the presence of supercooled liquid in Arctic clouds, and that prescribing temperature-dependent cloud phase in numerical models is not appropriate. Liquid-containing cloud occurs over the largest height range during JJA, from the surface to 7 km. During the transition seasons (MAM, SON), the most common liquid-containing clouds occur at a higher height and a lower temperature than during JJA.

[10] Over the high northern latitude oceans, most CALIPSO-GOCCP-detected ice clouds occur above 4 km and at temperatures between −30 and −60°C (Figures 2b and 2d). In contrast to similarities found between ground-based observations and CALIPSO-GOCCP for liquid-containing clouds, the lack of low-level ice-containing clouds in the CALIPSO-GOCCP observations appears inconsistent with ground-based observations. Ground-based observations reveal that many Arctic clouds are liquid-containing clouds that precipitate snow. Due to attenuation of its downward-pointing lidar beam, CALIPSO cannot detect snow falling below optically thick liquid-containing clouds. We verified that the downward-pointing lidar on CALIPSO cannot "see through" optically thick liquid-containing Arctic clouds to detect near-surface snow by plotting seasonal two-dimension histograms of scattering ratio (SR) and height (see auxiliary material).[1] Low-level liquid-containing Arctic clouds have large scattering ratios (SR > 20), attenuate the lidar beam, and prevent the detection of clouds below them. When the low-level liquid cloud fraction is small (e.g. in winter), CALIPSO observes more low-level (<3 km) ice-containing clouds and less undefined clouds. These results highlight that lidar attenuation must be taken into account when comparing surface- and space-based datasets.

4. Evaluation of a Climate Model Arctic Cloud Phase Using CALIPSO-GOCCP Observations and Simulator

[11] To illustrate that CALIPSO observations provide a new Arctic-wide constraint on cloud phase in climate models, we next present an example of the climate model evaluation enabled by CALIPSO-GOCCP cloud phase observations and associated enhancements to the CALIPSO simulator. Like Figures 2a–2d for the observations, Figures 2e–2h plot vertical distributions of liquid-containing and ice-dominated cloud amounts for LMDZ5B [*Hourdin et al.*, 2012], which is the atmospheric component of the Institut Pierre Simon Laplace (IPSL) coupled climate model. LMDZ5B reproduces the seasonal cycle of low-level liquid-containing clouds, with a maximum of occurrence in summer and a minimum occurrence during winter. But, in all but the summer months, LMDZ5B has too few liquid-containing clouds below 3 km and too many ice-containing clouds below 5 km when compared to CALIPSO-GOCCP observations. Also, the minimum temperature for liquid-containing clouds in the model is −10°C, while the observations show liquid-containing clouds down to −25°C.

[12] The results shown in Figures 2e–2h were obtained using a simulator to emulate the spaceborne observational process. As a result, the fact that LMDZ5B has insufficient

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL053385.

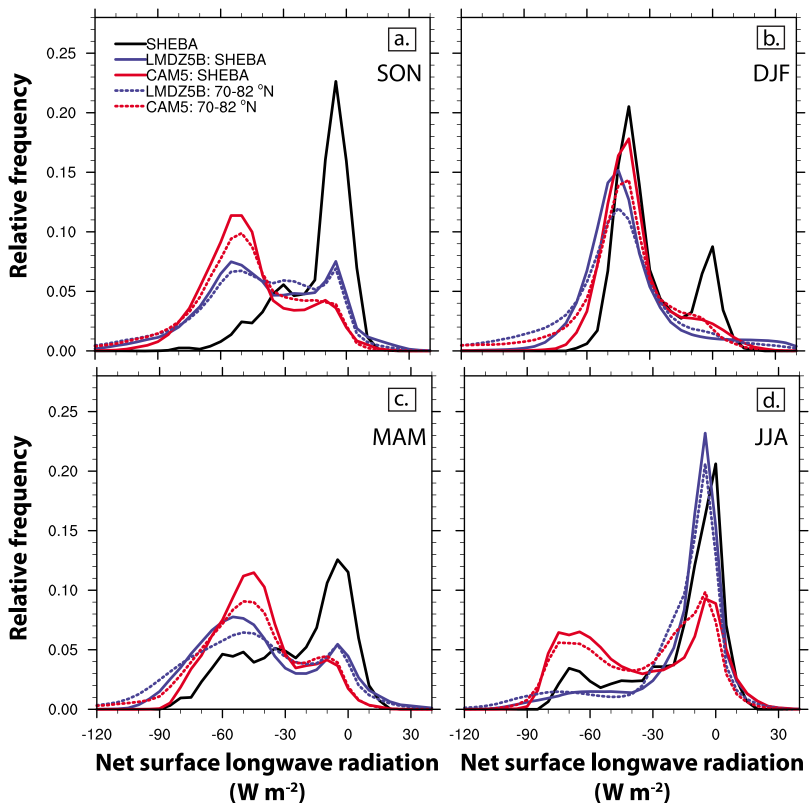

Figure 3. Probability density functions of hourly Arctic Ocean net (down minus up) surface longwave radiation by season in two climate models (LMDZ5B) [*Hourdin et al.*, 2012], CAM5 [*Neale et al.*, 2010], and SHEBA observations [*Persson et al.*, 2002]: (a) Fall (SON), (b) Winter (DJF), (c) Spring (MAM), and (d) Summer (JJA). Climate model SHEBA points based on averages over 70–80 N and 190–240 E, while SHEBA observations are taken along a single ship track (see Figure 1). LMDZ5B model data are 3-hour averages, while SHEBA observations and CAM5 model data are 1-hour averages.

liquid-containing clouds enhances near-surface ice cloud detection. Thus, one potential reason that LMDZ5B has more near-surface ice-containing clouds than the observations is because there is less optically thick cloud to attenuate the simulated lidar beam. However, the ice cloud fraction differences cannot entirely be explained by differences between modeled and observed lidar attenuation. For example, LMDZ5B appears to frequently predict unrealistically large ice cloud fractions at heights that are above the observed liquid-containing clouds, especially between 4 and 5 km.

5. Importance of Cloud Phase for Arctic Surface Radiation

[13] Two main findings have been presented so far. First, low-level liquid-containing clouds are ubiquitous in multi-year spaceborne lidar observations over much of the Arctic basin (Figures 1 and 2). Second, simulator-enabled climate model evaluation using CALIPSO-GOCCP cloud phase retrievals can reveal climate model cloud phase biases. Indeed, the one model that was evaluated had appreciable Arctic cloud phase biases, most notably: too little low-level liquid-containing cloud (Figure 2). While the utility of the hemispheric CALIPSO observations and simulator technique are demonstrated only for one model, the lack of liquid-containing clouds in this one model is not unique. Other non-simulator studies have used coastal ground-based observations to show that climate models typically under estimate liquid-containing cloud occurrence, especially in winter [e.g., *Prenni et al.*, 2007; *Liu et al.*, 2011]. To relate the importance of these cloud phase findings to Arctic surface climate, the influence of cloud phase on Arctic $F_{LW,NET}$ is next presented.

[14] Figure 3 shows $F_{LW,NET}$ distributions with the two peaks associated with a "radiatively opaque" state and a "radiatively clear" state from SHEBA. As SHEBA observations are only available for a single year (1997–1998) in a single location (Beaufort Sea), observational representativeness issues are important to address. Both the SHEBA location values and the Arctic Ocean values are shown for the models in Figure 3, and while there are differences, the qualitative character of the comparisons is not affected by them. Changing the number of years used to generate Figure 3 also didn't qualitatively change the climate model distribution shapes (not shown); however, with only a single year of SHEBA observations, a similar statement cannot be made based on observations. To fully evaluate the influence of cloud phase on radiation, many more in situ surface radiation observations over the Arctic Ocean are needed. The need for more in situ surface radiative flux observations over the Arctic Ocean is especially poignant given the rapid

changes in Arctic surface climate that have been observed and are projected to continue.

[15] LMDZ5B and the fifth version of the Community Atmosphere Model (CAM5) [*Neale et al.*, 2010] are included in Figure 3. Both climate models underestimate the occurrence of the "radiatively opaque" state in the $F_{LW,NET}$ as compared to SHEBA observations, especially during the non-summer months. Given the above findings and previous studies, it follows that the underestimation of liquid-containing cloud in LMDZ5B (Figure 2) helps explain the deficit of "radiatively opaque" states in LMDZ5B during non-summer months. During JJA, both the LMDZ5B liquid-containing cloud fraction and the LMDZ5B distribution of $F_{LW,NET}$ are a better match to CALIPSO-GOCCP and SHEBA observations respectively. The better agreement between JJA cloud phase and JJA radiation suggests getting the cloud phase right has an important influence on the ability of a climate model to get the surface radiation right.

[16] Unlike previous CAM versions that specified cloud phase as a function of temperature, CAM5 prognoses cloud phase and includes important processes such as explicit ice nucleation and the WBF process. Yet, even with representation of processes known to be important for the ice-liquid partitioning in clouds, CAM5 underestimates the occurrence frequency of the "radiatively opaque" state and overestimates the occurrence frequency of the "radiatively clear" state. An underestimation of cloud liquid water amounts in CAM5 is a known bias [*Liu et al.*, 2011; *Barton et al.*, 2012], and likely contributes to the inability of CAM5 to reproduce observed $F_{LW,NET}$ distributions shown in Figure 3.

[17] More generally, our limited evaluation of climate models participating in the most recent Coupled Model Inter-comparison Project (CMIP5) [*Taylor et al.*, 2012] (not shown) reveals that most climate models are not accurately representing the bimodality of $F_{LW,NET}$ in non-summer seasons. Only a very limited number of models reproduce the observed "radiatively opaque" peak during DJF. In the transition seasons (MAM, SON), many models have a "radiatively opaque" peak, but all still have a tendency to produce too many "radiatively clear" states. The JJA distribution comparisons were better, with only a limited number of models producing only "radiatively clear" states.

6. Summary and Implications

[18] This study presents new hemispheric multi-year (2006–2011) observations of ubiquitous liquid-containing Arctic clouds. These new CALIPSO-GOCCP cloud phase observations are used along with a lidar simulator to demonstrate the inability of a climate model to accurately recreate the amount of liquid-containing Arctic clouds. Liquid phase biases in this climate model limit its ability to reproduce observed distributions of net surface radiative fluxes. Evaluation of additional climate models suggests the lack of liquid-containing cloud and its impact on surface radiative fluxes is a common climate model deficiency. The simple prescribed relationships between cloud phase and temperature that have historically been used in climate models are incapable of reproducing the Arctic cloud phase observations described here. Moreover, even when advanced microphysical schemes that predict cloud phase are used, such as those currently used in CAM5, insufficient liquid water was predicted. The main strength of the CALIPSO-GOCCP Arctic cloud phase observations presented here is that they robustly document the frequent presence of liquid-containing clouds over much of the Arctic domain. When combined with a lidar simulator to replicate the observational process, CALIPSO-GOCCP cloud phase observations provide a new robust benchmark for climate model development efforts. Specifically, CALIPSO-GOCCP cloud phase retrievals enable modelers to move beyond evaluation of Arctic cloud occurrence and vertical structure and towards evaluation and improved simulation of Arctic cloud phase and surface radiative fluxes.

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References

Barton, N. P., S. A. Klein, J. S. Boyle, and Y. Y. Zhang (2012), Arctic synoptic regimes: Comparing domain wide Arctic cloud observations with CAM4 and CAM5 during similar dynamics, *J. Geophys. Res.*, *117*, D15205, doi:10.1029/2012JD017589.

Bergeron, T. (1935), *Proces Verbaux de l'Association de Meteorologie*, edited by P. Duport, pp. 156–178, Int. Union of Geod. and Geophys., Karlsruhe, Germany.

Bey, I., D. J. Jacob, R. M. Yantosca, J. A. Logan, B. D. Field, A. M. Fiore, Q. Li, H. Y. Liu, L. J. Mickley, and M. G. Schultz (2001), Global modeling of tropospheric chemistry with assimilated meteorology: Model description and evaluation, *J. Geophys. Res.*, *106*(D19), 23,073–23,095, doi:10.1029/2001JD000807.

Chepfer, H., S. Bony, D. Winker, M. Chiriaco, J.-L. Dufresne, and G. Sèze (2008), Use of CALIPSO lidar observations to evaluate the cloudiness simulated by a climate model, *Geophys. Res. Lett.*, *35*, L15704, doi:10.1029/2008GL034207.

Chepfer, H., S. Bony, D. Winker, G. Cesana, J. L. Dufresne, P. Minnis, C. J. Stubenrauch, and S. Zeng (2010), The GCM-Oriented CALIPSO Cloud Product (CALIPSO-GOCCP), *J. Geophys. Res.*, *115*, D00H16, doi:10.1029/2009JD012251.

de Boer, G., E. W. Eloranta, and M. D. Shupe (2009), Arctic mixed-phase stratiform cloud properties from multiple years of surface-based measurements at two high-latitude locations, *J. Atmos. Sci.*, *66*(9), 2874–2887, doi:10.1175/2009JAS3029.1.

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.

Doyle, J. G., G. Lesins, C. P. Thackray, C. Perro, G. J. Nott, T. J. Duck, R. Damoah, and J. R. Drummond (2011), Water vapor intrusions into the High Arctic during winter, *Geophys. Res. Lett.*, *38*, L12806, doi:10.1029/2011GL047493.

Findeisen, W. (1938), *Kolloid-Meteorologische*, 2nd ed., Am. Meteorol. Soc., Boston, Mass.

Hourdin, F., et al. (2012), LMDZ5B: The atmospheric component of the IPSL climate model with revisited parameterizations for clouds and convection, *Clim. Dyn.*, doi:10.1007/s00382-012-1343-y, in press.

Kay, J. E., and A. Gettelman (2009), Cloud influence on and response to seasonal Arctic sea ice loss, *J. Geophys. Res.*, *114*, D18204, doi:10.1029/2009JD011773.

Kay, J. E., et al. (2012a), Exposing global cloud biases in the Community Atmosphere Model (CAM) using satellite observations and their corresponding instrument simulators, *J. Clim.*, *25*, 5190–5207, doi:10.1175/JCLI-D-11-00469.1.

Kay, J. E., et al. (2012b), The influence of local feedbacks and northward heat transport on the equilibrium Arctic climate response to increased greenhouse gas, *J. Clim.*, *25*, 5433–5450, doi:10.1175/JCLI-D-11-00622.1, in press.

Klein, S. A., and C. Jakob (1999), Validation and sensitivities of frontal clouds simulated by the ECMWF model, *Mon. Weather Rev.*, *127*(10), 2514–2531, doi:10.1175/1520-0493(1999)127<2514:VASOFC>2.0.CO;2.

Liu, X., et al. (2011), Testing cloud microphysics parameterizations in NCAR CAM5 with ISDAC and M-PACE observations, *J. Geophys. Res.*, *116*, D00T11, doi:10.1029/2011JD015889. [Printed *177*(D1), 2012.]

Morrison, H., et al. (2012), Resilience of persistent Arctic mixed-phase clouds, *Nat. Geosci.*, *5*, 11–17, doi:10.1038/ngeo1332.

Neale, R. B., et al. (2010), Description of the NCAR Community Atmosphere Model (CAM 5.0), *Tech. Note 486+STR*, Nat. Cent. for Atmos. Res., Boulder, Colo.

Persson, P. O. G., C. W. Fairall, E. L. Andreas, P. S. Guest, and D. K. Perovich (2002), Measurements near the atmospheric surface flux group tower at SHEBA: Near-surface conditions and surface energy budget, *J. Geophys. Res.*, *107*(C10), 8045, doi:10.1029/2000JC000705.

Prenni, A. J., et al. (2007), Can ice-nucleating aerosols affect Arctic seasonal climate?, *Bull. Am. Meteorol. Soc.*, *88*, 541–550, doi:10.1175/BAMS-88-4-541.

Shupe, M. D. (2011), Clouds at Arctic atmospheric observatories, part II: Thermodynamic phase characteristics, *J. Appl. Meteorol. Climatol.*, *50*, 645–661, doi:10.1175/2010JAMC2468.1.

Shupe, M. D., and J. M. Intrieri (2004), Cloud radiative forcing of the Arctic surface: The influence of cloud properties, surface albedo, and solar zenith angle, *J. Clim.*, *17*, 616–628, doi:10.1175/1520-0442(2004)017<0616:CRFOTA>2.0.CO;2.

Shupe, M. D., S. Y. Matrosov, and T. Uttal (2006), Arctic mixed-phase cloud properties derived from surface-based sensors at SHEBA, *J. Atmos. Sci.*, *63*(2), 697–711, doi:10.1175/JAS3659.1.

Stramler, K., A. D. Del Genio, and W. B. Rossow (2011), Synoptically driven Arctic winter states, *J. Clim.*, *24*, 1747–1762, doi:10.1175/2010JCLI3817.1.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl (2012), An overview of CMIP5 and the experiment design, *Bull. Am. Meteorol. Soc.*, *93*, 485–498, doi:10.1175/BAMS-D-11-00094.1.

Uttal, T., et al. (2002), Surface heat budget of the Arctic Ocean, *Bull. Am. Meteorol. Soc.*, *83*, 255–276.

Wegener, A. (1911), *Thermodynamik der Atmosphare*, J. A. Barth, Leipzig, Germany.

Winker, D. M., et al. (2009), Overview of the CALIPSO mission and CALIOP data processing algorithms, *J. Atmos. Oceanic Technol.*, *26*, 2310–2323, doi:10.1175/2009JTECHA1281.1.

Winton, M. (2006), Amplified Arctic climate change: What does surface albedo feedback have to do with it?, *Geophys. Res. Lett.*, *33*, L03701, doi:10.1029/2005GL025244.