Description of Mixed-Phase Clouds in Weather Forecast and Climate Models

Michael Tjernström
Department of Meteorology, Stockholm University, SE-106 91 Stockholm, Sweden
phone: +46 (0)8 163110 fax: +46 (0)8 157185 email: michaelt@misu.su.se

Award Number: N000141210235
http://www.ascos.se
http://www.swerus-c3.geo.su.se/

LONG-TERM GOALS

To develop improved parameterizations of so-called mixed-phase stratocumulus in numerical models of weather and climate, and of their impact on the surface energy budget over the Arctic Ocean, their impact on the vertical structure of the lower troposphere and relationships to larger-scale meteorology.

OBJECTIVES

Develop a process-level understanding addressing the processes responsible for making mixed-phase stratocumulus so common, by far the most common cloud type over the Arctic, when thermodynamic principles suggest that ice and liquid particles cannot coexist for extended periods of time. Find linkages between dynamic processes on all scales, ranging from long range transport to turbulent motions, and cloud micro-physics.

APPROACH

Developing new parameterizations is a multi-scale and multi-tool endeavor that links investigations of field observations to analysis of meteorology, process-level modeling and full-scale numerical modeling. This project takes its cue from field experiments, primarily from the *Arctic Summer Cloud Ocean Study* (ASCOS), a summer expedition on the Swedish icebreaker Oden during the summer of 2008 and a part of the International Polar Year, and extends to the *Arctic Clouds in Summer Experiment* (ACSE) in summer 2014, also on the icebreaker Oden. ACSE is part of a larger effort, focusing on greenhouse gas exchange in the Arctic: the SWERUS-C3 expedition.

From both campaigns, we rely on a combination of surface based in-situ observations, for example, the components of the surface energy budget and profiles from radiosoundings, and a suite of advanced surface-based remote sensing instrumentation, using Doppler radar, lidar and micro-wave radiometry, to observe the clouds. The remote sensing instruments allow detailed estimates of the cloud-properties such as dynamics, bulk properties as well as cloud micro-physics at high resolution in time and vertical space. Understanding gained from field the analysis of field experiment data will be generalized using process modeling (Large Eddy Simulation, LES) and GCMs (e.g. OpenIFS or EC-Earth).

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2014**	2. REPORT TYPE	3. DATES COVERED **00-00-2014 to 00-00-2014**

4. TITLE AND SUBTITLE **Description of Mixed-Phase Clouds in Weather Forecast and Climate Models**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Stockholm University,Department of Meteorology,SE-106 91 Stockholm, Sweden,**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

This is a highly collaborative project that rests on expertise and collaborations gained over the last decade or more. Key staff at Stockholm University beside the PIs (Profs. Michael Tjernström and Gunilla Svensson), include PhD students (Georgia Sotiropoulou, funded by this grant, and Cecilia Wesslèn, currently on parental leave), post-docs (Dr. Joseph Sedlar, for analysis of experimental data and operational ACSE coordination, and Dr. Julien Savre for LES/CRM modeling), and Dr. Annica Ekman who is working with the LES/CRM modeling and is an expert on aerosol/cloud interaction. For logistics during ACSE we interact with Profs. Martin Jakobsson and Örjan Gustavsson, Stockholm University, as Lead PIs for SWERUS-C3; this field program is a flag-ship project for the Bolin Centre for Climate Research at Stockholm University.

For the ACSE field phase and the first analysis of data we rely on two external partner groups; Drs. Matthew Shupe and Ola Persson at CIRES and NOAA/ESRL in Boulder, Colorado, for the remote sensing instrumentation, and Dr. Ian Brooks and his group from Leeds University in Leeds, UK, for surface energy observations and additional remote sensing equipment. They of course also rely on their coworkers and support staff at their institutes.

WORK COMPLETED

The analysis of ASCOS data and modeling work described in previous reports has continued, however, the main milestone achieved during the last year was the conclusion of the ACSE on the icebreaker Oden, during the SWERUS-C3 expedition. Below the ongoing analysis modeling is briefly summarized first, and then the expedition is described, although it is too early yet to report on proper results.

Some science work was completed based on the ASCOS campaign in 2008, which is of large importance to this project although not funded by this grant. A survey of summer Arctic meteorology from several expeditions (Tjernström et al. 2012) and well as a comprehensive ASCOS overview (Tjernström et al. 2013) were completed. A study using data from ASCOS, SHEBA and from Barrow compiled to relate the vertical thermodynamic structure to the clouds (Sedlar et al. 2012) also relied heavily on ASCOS data; this study was followed by a more general study that was recently accepted (Sedlar 2014). Two studies have emerged examining the coupling nature between mixed-phase cloud and turbulence generated in the shallow boundary during ASCOS. Shupe et al. (2013) developed a dynamic-based methodology, while Sotiropoulou et al. (2014) utilized a thermodynamic methodology to examine the impact of cloud and thermodynamic properties relative to the coupling state. A study examining the frequency characteristics of in-cloud vertical velocity variance relative to the surface-cloud coupling nature (Sedlar and Shupe 2013) was also published.

The evaluation studies of two versions of the *Arctic System Reanalysis* (ASR) and the ECMWF ERA-Interim reanalysis (Wesslèn et al. 2013), as well as multiple reanalyzes and global climate model simulations (de Boer et al. 2013) has been followed by further modeling evaluation and study in collaboration with ECMWF. In this, the new moist phsyics package of the IFS was run in several dedicated semi-reanalysis mode runs to explore how if and how new scheme improved the results. One paper on EC-Earth was also published (Koenik et al. 2012). For the large-eddy similuation work, the MIMICA LES, developed at MISU, took part in the ISDAC model intercomparison (Ovchinnikov et al. 2014); a sensitivity test extension based on this case was also published (Savre et al. 2014). An LES study of data from ASCOS is also under way.

The main milestone accomplished during the last year was the succefull completion of ACSE. The SWERUS-C3 expedition, that ACSE was part of, departed on the icebreaker Oden from Tromsö, Norway, on 5 July and traversed the Siberian Shelf (through the Barents, Karam Laptev and East Siberian Sea) and arrived in Barrow, Alaska, on 19 August. In Barrow a crew and science staff rotation was executed. Oden departed again on August 22 and traversed back along the outher shelf and Lomonosov Ridge and returned to Tromsö on 5 October.

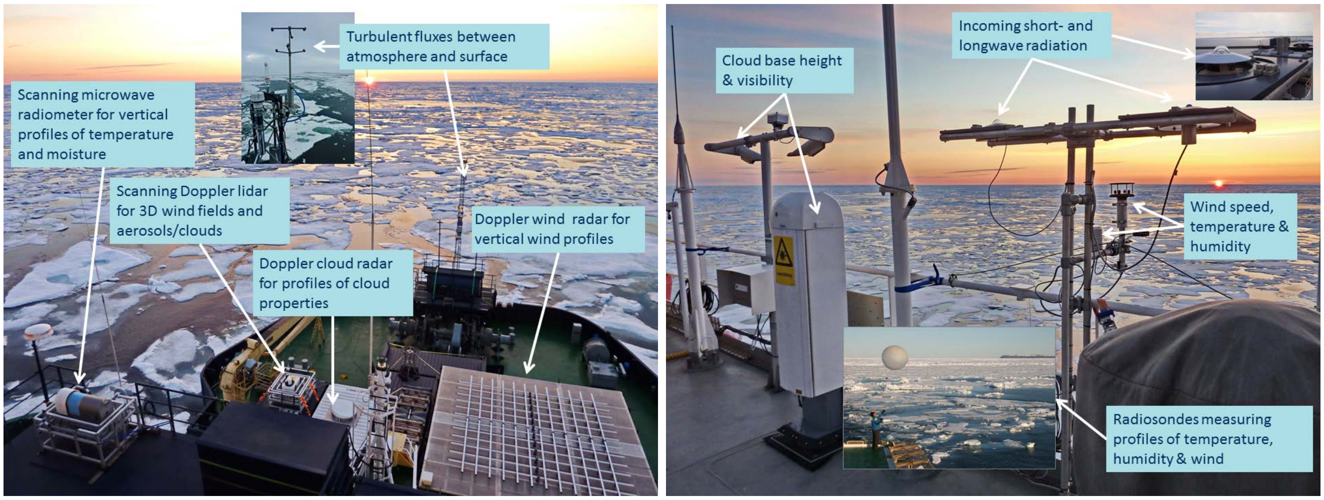

Figure 1. Photo overview of some instruments deployed on the Oden for ACSE showing (left) remote sensing instruments and bow mast from the 7th top deck, and (right) instruments on the 7th deck and sounding relese on the helideck of Oden.

Figure 2. Photot of Oden instrumentation from the bow mast.

An extensive suit of instruments was operated during the entire expedition. The remote sensing instrument included a vertically pointing W-Band Doppler cloud radar, a 449MHz phased-array Doppler wind radar, a 3D scanning Doppler lidar, a two scanning microwave radiometers as well as several cloud celioemeters, visibility sensors and IR surface temperature sensors. The insitu instruments included a full weather station, incoming surface radiation, eddy-covariance turbulence flux observations on a bow mast 20 meters above the surface and 6-hourly radiosonde releases; the latter was transimtted to the GTS by email over Iridium satellite telephone. Figures 1 and 2 include photos of some of these instruments.

In addition a waverider bouy and the “sea snake” SST devide was operated in open water and near ice when conditions allowed. The data is currently undergoing post processing and quality assurance and most results will come later.

RESULTS

Observational results: The main resulst from the analysis of the dynamics of mixed-phase clouds is summarized as follws. Low-level stratocumulus domainte the clouds during the central Arctic summer; these are oiften mixed-phase, with a thin liquid layer precipitating ice. The surface based boundary-layer is most often shallow and well-mixed, and the dominating term in the surface energy balance is the net radiation, which is to a first order is modulated by these clouds. For most of the summer, these clouds contribute to the ice melt; the few cloud free episodes leads to a surface cooling. However, the stratocumus is most often not connected to the surface based boundary layer; instead the clouds themselves generates a mixed layer insoide and often below the clouds that c:a 40% of the time is *not* connected with the surface turbulence. In addition to the coupled and decoupled stratocumulus regimes, that together are the most important (70% of the time), we also discovered a third; a stable cloud regime, where the stratification through the clouds is stable and mixing diminished. These clouds are always found in proximity to the surface, not seldom as fog, they are not mixed-phase and occurs when the observed CCN concentrations are low; hence we hypothesize that these are related to optically thin conditions. This is the explanation for why cloud-top cooling and consequent cloud-overturning mixing does not occur. This stable class of clouds seems to occur ~30% of the time.

Main modeling results: Many models overestimate low clouds in the Arctic summer and fail to reproduce the observed dynamic decoupling from the surface of the clouds. There are also other systematic biases in all the models, both climate models and forecast models such as those used for reanalysis. For example, ERA-Interim has a signidicant and difficult to explain boundary-layer warm bias in summer of over 1K. It does produce clouds rouchly when it should, but the clouds have too little liquid watr and much to much ice, and also the model fail to dissipate clouds when the observations show dissipation, even though the general meteorology seems to be correct. The ASR, on the other hand, glaciate mixed-phase clouds rapidly and has a tendency to too often dissipate the low clouds entirely, leading to a substantial cold bias. The new moist phsyics scheme in the IFS improves the modeling of liquid water and greatly improves the cloud ice in the IFS, compared to the model version used in ERA-Interim; however, and somewhat difficult to explain, this does not seem to improve much many of the other biases of the boundary layer or surface energy budget. It does improve the layering of the clouds somewhat, and increasing the resolution also helps, but neither the lack of decoupling, the tendency to not dissipate clouds when it should, nor the surface radiation budgets are improved. This work will continue; a manuscript is being written and futher studies into the cloud microphsyics and the boundary-layer turbulence schemes are planned in collaboration with scientists at the EECMWF.

Over-all, the distribution of clouds and visibility in ACSE conforms to those from earlier summertime strudies (e.g. Tjernström et al. 2012). Figure 3 illustrates the probabilities of lowest cloud base height abd visibility for the entire expedition. Low cloud bases dominate and the visibility show the bimodal distribution common in the Arctic, with frequent fog and otherwise very good visibility, i.e. an almost complete absence of haze. The weak relative peak in the pprobability ~10 km visibility is mostly coming from open water areas off the Siberian coast, where either continental aerosols or sea-salt aerosols can be expected to be relatively more important.

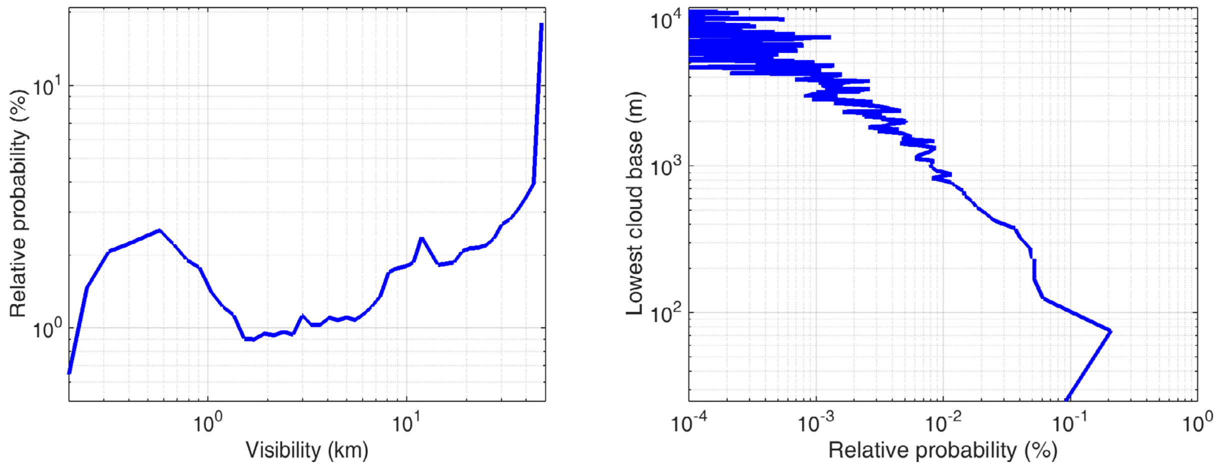

Figure 3. Statistics for the (left) horizontal visibility, and (right) lowest cloud base height.

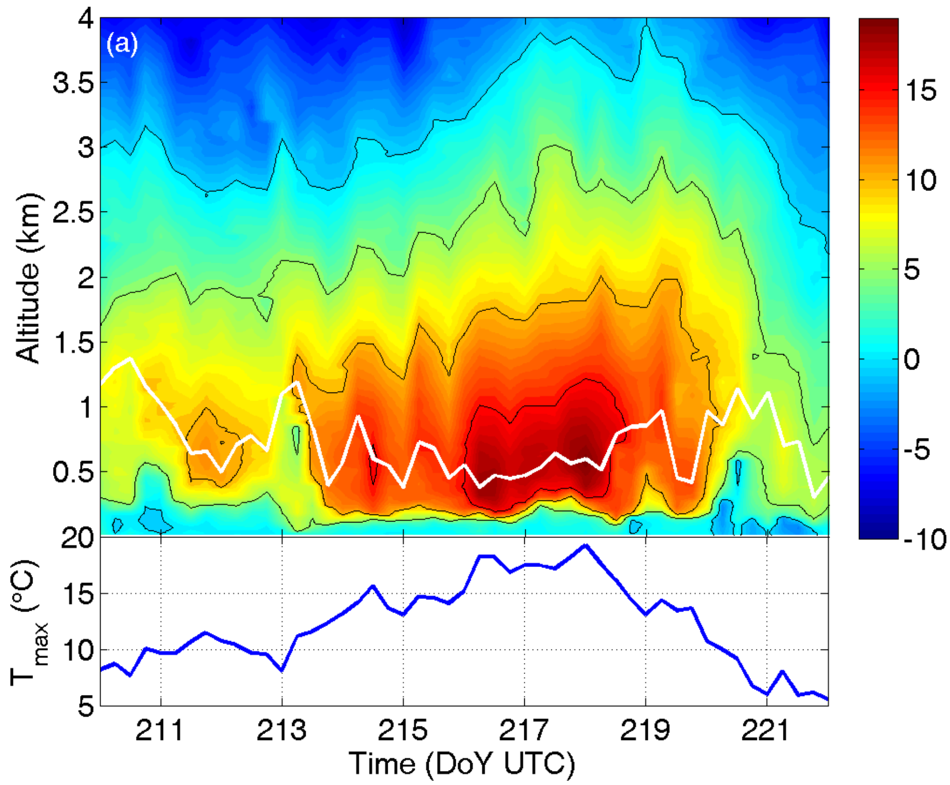

Figure 4. Top panel shows a time-height cross section of temperature from soundings, while lower panel shows the maximum temperature in the surface inversion. The white line in the contour plot indicates the height of this temperature. Time is given as Day of the Year, with DoY=1.0 at 00UTC on 1 January

Dividing the ACSE observations into two; before and after the Barrow rotation, as a proxy for late summer and early fall, summer measurements showed energy flux surpluses leading to significant surface melt. In particular during one week-long episode, with warm air advected from the Siberian inland, the air mass transformation as the warm air enters the melting ice gave rise to an extremely strong surface inversion (Figure 4). In this warm air, fog forms which enhance the downward longwave radiation while the stratification enhances the downward turbulent flux of sensible heat. Preliminary calculations indicate this contributes to an additional heat flux to the surface of 10-20 Wm^{-2} which contributes to rapid thinning of the ice.

Early autumn, late August and September, measurements in contrast showed surface energy balance deficits, leading to freeze-up of both sea ice and the ocean surface. The surface albedo and processes impacting the energy content of the upper ocean appear key to producing a temporal difference between the freeze-up of the sea-ice surface and adjacent open water. While synoptic conditions, atmospheric advection, and the annual solar cycle have primary influence determining when energy fluxes are conducive for melt or freeze, mesoscale atmospheric phenomena unique to the ice edge region appear to also play a role. These observations suggest a scenario of key processes important for the annual evolution of melt and freeze-up.

IMPACT/APPLICATIONS

Summarizing the results from all of these studies, they indicate that processes that are responsible for modulating the lonwave radiation at the surface are most important; more so than the modulation of the solar radiation, although the summer melt is of course primarely caused by the solar radiation being present in summer. The presence of clouds is of course the most important aspects of this; although clouds reduce net solar radiation, the increased net thermal radiation leads to a surface warming effect. This also means that changes to the aerosol climate favoring optically thick clouds (more liquid water, more and smaller droplets) may actually enhance the warming as the estimated 30% optically thin clouds turns “thick” and hence the longwave radiation is enhanced. Finally, the most important aspects of the atmospheric long-range transport is probably in transporting water vapor that can increase clouds and liquid water in already present clouds. Finally several analyses now indicate that the onset of melt and freeze is not a gradual process, but is directly associated with episodic atmospheric events.

Modeling has many problems to solve to minimize the sometimes rather large biases, but in the context of this study, we have shown that descrptions of clouds that are based on separating the condensed water into prognostic equations for cloud liquid and ice, rain and snow, requires very careful tuning, or the system witll galciate and the clouds dissapear. Also the results indicate that it may be necessary to relaxe prescribed assumption on CCN concentration so that clouds may become optically thin or dissipate appropriately (cf. e.g. Birch et al. 2012). The modeling of clouds also generates clouds that are to tightly coupled to the surface which may be serious, in summer when the surface conditions are so tightly controlled by the melt and in winter when several feedbacks may occur in a model that may not be present in reality.

RELATED PROJECTS

This project is a follow-up of important meteorological parts of ASCOS (www.ascos.se) and a part of the SWERUS-C3 field program (http://swerus-c3.geo.su.se/); SWERUS-C3 is a flag-ship project in the Bolin Centre for Climate Research (www.bolin.su.se). A future program of which ASCE may be seen as a pilot project is the MOSAiC program (www.mosaicobservatory.org). On the modeling side, ASCE is related to the Arctic System Reanalysis (http://polarmet.osu.edu/ASR/), the EC-Earth program (http://ecearth.knmi.nl/) and the EUCLIPSE EU-project (www.euclipse.eu/index.html).

REFERENCES AND PUBLICATIONS

Birch, C.E. , I.M. Brooks, P. Earnshaw, C. Leck, A.P. Lock, T. Mauritsen, P.O.G. Persson, S.F. Milton, . Sedlar, M. Shupe and M. Tjernström, 2012: Modelling cloud and atmospheric structure in the central Arctic: ASCOS case studies, *Atmospheric Chemistry and Physics Discussions*, **12**, 12, 3419–3435, 2012, www.atmos-chem-phys.net/12/3419/2012/doi:10.5194/acp-12-3419-2012, [published, refereed]

de Boer, G., M.D. Shupe, P.M. Caldwell, S.E. Bauer, P.O.G. Persson, J.S. Boyle, M. Kelley, S.A. Klein and M. Tjernström, 2013: Near-surface meteorology during the Arctic Summer Cloud Ocean Study (ASCOS): evaluation of reanalyses and global climate models, Atmos. Chem. Phys. Discuss., 13, 19421-19470, doi: 10.5194/acpd-13-19421-2013 [published, refereed]

Devasthale, A., J. Sedlar, and M. Tjernström, 2011: Characteristics of water-vapour inversions observed over the Arctic by Atmospheric Infrared Sounder (AIRS) and radiosondes**.** *Atmospheric Chemistry and Physics*, **11**, 9813–9823, www.atmos-chem-phys.net/11/9813/2011/doi:10.5194/acp-11-9813-2011 [published, refereed]

Koenigk, T., L. Brodeau, M. Caian, R. Döscher, R.G. Graversen, J. Karlsson, G. Svensson, M. Tjernström, U. Willén, K. Wyser, 2012: Arctic Climate Change in the 21st Century in an Ensemble of AR5 Scenario Projections with EC-Earth, *Climate Dynamics*, Early on-line, DOI 10.1007/s00382-012-1505-y, [published, refereed]

Ovchinnikov, M., A. S. Ackerman, A. Avramov, A. Cheng, J. Fan, A. M. Fridlind, S. Ghan, J. Harrington, C. Hoose, A. Korolev, G. M. McFarquhar, H. Morrison, M. Paukert, J. Savre, B. J. Shipway, M. D. Shupe, A. Solomon and K. Sulia, 2014: Intercomparison of large-eddy simulations of Arctic mixed-phase clouds: Importance of ice size distribution assumptions, JAMES, 6, , 223–248, DOI: 10.1002/2013MS000282, [published, refereed]

Savre, J., A. M. L. Ekman, G. Svensson and M. Tjernström, 2014: Large-eddy simulations of an Arctic mixed-phase stratiform cloud observed during ISDAC: sensitivity to moisture aloft, surface fluxes and large-scale forcing, Quart. J. Roy. Met. Soc., Early On-Line, DOI: 10.1002/qj.2425, [published, refereed]

Sedlar, J., MT, T. Mauritsen, M. Shupe, I. Brooks, P. Persson, C. Birch, C. Leck, A. Sirevaag, and M. Nicolaus, 2011: A transitioning Arctic surface energy budget: the impacts of solar zenith angle, surface albedo and cloud radiative forcing. *Climate Dynamics*, **37**, 1643–1660, doi:10.1007/s00382-010-0937-5, [published, refereed]

Sedlar, J., M. D. Shupe and M. Tjernström, 2012: On the relationship between thermodynamic structure and cloud top, and its climate significance in the Arctic. *Journal of Climate*, **25**, 2374-2393, DOI 10.1007/s00382-010-0937-5, [published, refereed]

Sedlar, J. and M.D. Shupe, 2013: Characteristics of vertical motions observed in Arctic mixed-phase stratocumulus, manuscript, Atmos. Chem. Phys., 14, 3461–3478, www.atmos-chem-phys.net/14/3461/2014/doi:10.5194/acp-14-3461-2014, [published, refereed]

Sedlar, J., 2014: Implications of limited liquid water path on static mixing within Arctic low-level clouds J. App. Met. Clim. [In press, refereed]

Shupe, M. D., I. M. Brooks, and G. Canut, 2012: Evaluation of turbulent dissipation rate retrievals from Doppler Cloud Radar, Atmos. Meas. Tech., 5, 1375–1385, doi: 10.5194/amt-5-1375-2012, [published, refereed]

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. Discuss., 13, 13191-13244, doi: 10.5194/acpd-13-13191-2013, [published, refereed]

Sotiropoulou, G., M. Tjernström, J. Sedlar and M.D. Shupe, 2014: Cloud mixing regimes in Arctic summer low-level clouds, Atmos. Chem. Phys.[accepted, refereed]

Tjernström, M., C.E. Birch, I.M. Brooks, M.D. Shupe, P.O.G. Persson, J. Sedlar, T. Mauritsen, C. Leck, J. Paatero, M. Szczodrak and C.R. Wheeler, 2012: Meteorological conditions in the central Arctic summer during the Arctic Summer Cloud Ocean Study (ASCOS), Atmos. Chem. Phys., 12, 6863–6889, doi: 10.5194/acp-12-6863-2012, [published, refereed]

Tjernström, M., and coauthors, 2013: The Arctic Summer Cloud-Ocean Study (ASCOS): overview and experimental design, Atmos. Chem. Phys., 14, 2823–2869, www.atmos-chem-phys.net/14/2823/2014/doi:10.5194/acp-14-2823-2014, [published, refereed]

Wesslén, C., M. Tjernström, D.H. Bromwich, G. de Boer, A.M.L. Ekman, L.-S. Bai and S.-H. Wang, 2013: The Arctic summer atmosphere: an evaluation of reanalyses using ASCOS data, Atmospheric Chemistry and Physics, 14, 2605–2624, www.atmos-chem-phys.net/14/2605/2014/doi:10.5194/acp-14-2605-2014, [published, refereed]