

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

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LONG-TERM GOALS

To develop an improved parameterization 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 a new expedition in summer 2014, also on the icebreaker Oden: the *Arctic Clouds in Summer* (or ACSE) experiment. 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) & Cloud Resolved Modeling (CRM)) and the resulting parameterizations will be tested in the US Navy COAMPS regional model before being migrated to GCM (e.g. OpenIFS, EC-Earth or NAVGEMS).

This is a highly collaborative project that rests on expertise and collaborations gained over the last decade or more. Keystaff at Stockholm University, beside the PIs (Profs. Michael Tjernström and Gunilla Svensson), involve two PhD students (Georgia Sotiropoulou, funded from this grant, and Cecilia Wesslèn, working on ASCOS data), two 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 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, we rely on external partners; Drs. Matthew Shupe and Ola Persson at NOAA/ESRL in Boulder, Colorado, for the remote sensing instrumentation, and on 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

Funding for the field program must be a priority for icebreaker based field work in the Arctic and is ongoing until the icebreaker leaves the harbor; the present grant is a very important part of this but the bulk of the logistics funding including all the ship time comes through funding for SWERUS-C3, from the *Knut and Alice Wallenberg Foundation* and the *Swedish Secretariat for Polar Research*. The Swedish Research Council's Infrastructure board funds some of the installation on *Oden* and also some research.

For ACSE, the NERC proposal in the UK, led by Dr. Ian Brooks, was funded and will cover the turbulence instruments, a portion of radiosoundings and a number of shipped-based remote sensors for observing aerosol, cloud properties and thermodynamics. However, the proposal to the *National Science Foundation* in the US, for the essential remote sensing instruments failed. Since this is an essential part of ACSE, we have managed to secure the necessary funding from the *Faculty of Science* and the *Department of Meteorology*, both at Stockholm University.

Science work has been completed following the successful ASCOS campaign, 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. 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. (2013) utilized a thermodynamic methodology to examine the impact of cloud and thermodynamic properties relative to the coupling state. Furthermore, a study examining the frequency characteristics of in-cloud vertical velocity variance relative to the surface-cloud coupling nature will be submitted prior to the end of this year (Sedlar and Shupe 2013). Preliminary work on the boundary-layer structure and how it relates to

clouds will be summarized in a paper later this year (Brooks et al. 2013). One novel feature of this work is the creation of a time-height cross-section of “observed” *Richardson number*, based on observations, from temperature soundings by a scanning microwave radiometer, complemented by cloud phase information from the cloud radar, and wind information from a combination of Doppler sodar and wind profiler data. To our knowledge, this has never been accomplished before from observations.

A study on the performance of two versions of the *Arctic System Reanalysis* (ASR; Wesslèn et al. 2013) and multiple reanalyses and global climate model simulations (de Boer et al. 2013) in simulating meteorology and clouds using data from ASCOS have also been completed and published in ACPD; these papers are under review for ACP. Finally, several studies of the performance of the CMIP5 models in the Arctic are near completion; one paper on EC-Earth was published (Koenig et al. 2012).

RESULTS

Many of the results that have been published so far are entirely based on outcomes from the ASCOS field project and are part of this effort, which is not funded by this grant but still falls within the efforts of this project. A summary of all these results can be found in a joint special issue across Atmospheric Chemistry and Physics, Ocean Sciences and Atmospheric Measurement Techniques (Copernicus Scientific Publishing). Some of this work is also including other data, from e.g. Barrow and ISDAC.

Complementing an overview and comparison of meteorological conditions during ASCOS with several past expeditions (Tjernström et al. 2012), Tjernström et al. (2013) present a full interdisciplinary overview of ASCOS methodology, as well as a meticulously-detailed description of instrumentation and targeted physical processes during ASCOS. This paper also summarizes some of the main outcomes from published ASCOS-related studies across disciplines, including oceanography, micro-biology, aerosol and chemical sciences, and meteorology.

The successful derivation of turbulent motions within mixed-phase stratocumulus cloud and precipitation layers from Doppler radar profiles (Shupe et al. 2012) at ASCOS lead to a study deriving cloud-driven vertical mixing depth below cloud base. Shupe et al. (2013) used turbulent dissipation rates in cloud and precipitation from Doppler radar observations to estimate the extent of vertical mixing from the cloud layer toward the surface. Based on one-week of low-level mixed-phase stratocumulus at ASCOS, Shupe et al. (2013) quantified that turbulence generated by the surface, and buoyancy-driven turbulence from cloud top radiative cooling, were essentially disconnected for nearly 75% of the entire week, corroborating previous results from ASCOS and other Arctic observatories (Sedlar et al. 2012); full coupling between cloud layer and surface occurred less frequently, often when cloud base height was physically closer to the surface. With the inclusion of helicopter profiles and ship-based CCN number concentrations, the authors conclude that the transport of CCN and IN particles aloft may be more critical to mixed-phase cloud lifetime as opposed to sources of particles near the surface.

As an extension on the question of coupling between surface and cloud layer, Sotiropoulou et al. (2013) developed a methodology to examine the thermodynamic coupling between cloud and surface independent of the method of Shupe et al. (2013); this study also utilized data from the full ASCOS transit and ice-drift, slightly more than one month of observations. Sotiropoulou et al. (2013) confirmed the dominance of a decoupled cloud-surface system, however, they were able further segregate decoupled clouds into either a weak decoupling with a shallow cloud-driven mixed-layer, or strongly decoupled with a deeper cloud-driven mixed layer. The latter often occurred when the cloud base was

higher above the surface; positive correlations were found between the cloud mixed-layer depth and cloud thickness, base, and top heights. Importantly, these two cases have dramatically different hydro-meteor and thermodynamic compositions in the sub-cloud layer, suggesting either advection and/or diabatic processes may be contributing to the lack of thermodynamic coupling. Both Shupe et al. (2013) and Sotiropoulou et al. (2013) have made substantial enhancements in understanding the controlling processes of coupling between cloud and surface, lending further support that the source of moisture (Devasthale et al. 2011) and aerosols may be dominated by advective fluxes aloft rather than fluxes from the surface. Sotiropoulou et al. (2013) also extended the cloud/boundary layer characterization to a stable regime, and showed that cases with stable stratification through the cloud most often were for small liquid water paths and clouds close to the surface; so called optically thin clouds. They hypothesize that for these cases the clouds have insufficient cloud water to generate the longwave radiation cloud-top cooling necessary for buoyancy generated cloud-overturning turbulence and hence mixing.

Sedlar and Shupe (2013) derived and examined the temporal characteristics of vertical velocity within ASCOS mixed-phase stratocumulus from Doppler radar. Using a plethora of statistical methods, the study characterized the dominant time scales of cloud-driven vertical motions and related them to changes in meteorological forcing and the coupling nature between cloud and surface. Although mesoscale forcing and an array of overhead sky conditions were shown to have the largest impact on vertical velocity variance, Sedlar and Shupe (2013) observed a weaker, yet statistically significant, relationship between cloud-driven vertical motions and the thermodynamic coupling state; vertical velocity variances tended to occur on slightly faster time scales (4-5 min) when the cloud and surface were thermodynamically coupled as opposed to decoupled (~ 8 min). Additionally, the study identified vertical coherency in velocity variance at different levels within the cloud layer, and the extension of the cloud layer into the temperature inversion (Sedlar et al. 2012) clearly has a direct impact on the absolute vertical velocity variance magnitude and skewness profile.

Wesslén et al. (2013) examined the ability of two versions of the ASR and ERA-Interim to simulate the local atmospheric, cloud and thermodynamic properties relative to ASCOS. They report that ERA-Interim, which is the global product forcing the regional ASR, generally performs better in describing some of the event-like features that were found from ASCOS, but also has significant systematic errors, while versions of the ASR, with higher spatial resolution and more advanced model physics, have smaller systematic errors but fail in some important event-like features; interestingly the largest error was the lack of simulated clouds during the week-long episode with mixed-phase stratocumulus discussed earlier in this report. This period was critical to the preconditioning of the surface via impacts on the surface energy budget for the onset of the seasonal ice freeze-up (Sedlar et al. 2011) and has been the focal period for a number of case studies (Birch et al. 2012; Shupe et al. 2013; Sedlar and Shupe 2013). None of the ASR versions form mixed-phase clouds during this period; instead they have clear conditions and much too low surface temperatures (Wesslén et al. 2013) in response to the lacking surface radiative cloud forcing. Another study evaluating both reanalyses and global climate simulations against ASCOS arrives at similar conclusions: the models and reanalyses succeed in capturing the large-scale meteorology (pressure and winds); however severe biases in low-level thermodynamics and stability yield large errors in cloud occurrence and phase, causing critical biases in the surface energy budget components (de Boer et al. 2013).

Dr. Julien Savre successfully implemented ice-phase microphysics within the MIT CRM and run baseline and sensitivity studies examining the profile budgets for the ISDAC mixed-phase cloud case; results are currently being written into two manuscripts. We initiated a baseline run for a chosen

mixed-phase ASCOS case, focusing on the role of cloud-driven mixing on the connection, or lack thereof, with surface-generated turbulence. Dr. Joseph Sedlar has also begun examining the role of heat and moisture exchange at the base of the cloud-driven mixed layer, and its role in developing stable thermodynamic structure, using a combination of thermodynamic principles and model simulations from the WRF model run in LES mode.

Preparations for the field phase of ACSE are now accelerating. As a result of infrastructure funding from the Swedish Research Council, a 10+ mast has been designed for the bow of the icebreaker *Oden* with a sky-lift solution to servicing instruments; this will be field tested this winter. ACSE will hold a planning workshop in Stockholm 20-23 November 2013, sponsored by the International Meteorological Institute at Stockholm University.

IMPACT/APPLICATIONS

Better treatment of clouds in model simulations of the Arctic is the number one important issue for understanding the impacts of individual components on the surface energy budget and thus the melting and freezing of sea ice, both at present and into the future.

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://eearth.knmi.nl/>) and the EUCLIPSE EU-project (www.euclipse.eu/index.html).

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