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Polarized view of supercooled liquid water clouds

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ABSTRACT

Supercooled liquid water (SLW) clouds, where liquid droplets exist at temperatures below 0°C present a well-known aviation hazard through aircraft icing, in which SLW accretes on the airframe. SLW clouds are common over the Southern Ocean, and climate-induced changes in their occurrence is thought to constitute a strong cloud feedback on global climate. The two recent NASA field campaigns POlarimeter Definition EXperiment (PODEX, based in Palmdale, California, January–February 2013) and Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys (SEAC4RS, based in Houston, Texas in August–September 2013) provided a unique opportunity to observe SLW clouds from the high-altitude airborne platform of NASA's ER-2 aircraft. We present an analysis of measurements made by the Research Scanning Polarimeter (RSP) during these experiments accompanied by correlative retrievals from other sensors. The RSP measures both polarized and total reflectance in 9 spectral channels with wavelengths ranging from 410 to 2250 nm. It is a scanning sensor taking samples at 0.8° intervals within 60° from nadir in both forward and backward directions. This unique angular resolution allows for characterization of liquid water droplet size using the rainbow structure observed in the polarized reflectances in the scattering angle range between 135° and 165°. Simple parametric fitting algorithms applied to the polarized reflectance provide retrievals of the droplet effective radius and variance assuming a prescribed size distribution shape (gamma distribution). In addition to this, we use a non-parametric method, Rainbow Fourier Transform (RFT), which allows retrieval of the droplet size distribution without assuming a size distribution shape. We present an overview of the RSP campaign datasets available from the NASA GISS website, as well as two detailed examples of the retrievals. In these case studies we focus on cloud fields with spatial features varying between glaciated and liquid phases at altitudes as high as 10 km, which correspond to temperatures close to the homogeneous freezing temperature of pure water drops (about -35°C or colder). The multimodal droplet size distributions retrieved from RSP data in these cases are consistent with the multi-layer cloud structure observed by correlative Cloud Physics Lidar (CPL) measurements.

1. Introduction

The existence of liquid water at temperatures well below 0°C was first described by Fahrenheit (1724). Because of the decrease in entropy associated with forming a crystal, the nucleation barrier is only surpassed readily at temperatures that depend on the size of the water drop; pure water drops of diameter 2 and 200 μm freeze homogeneously at respective temperatures of about -40°C and -35°C (Fig. 7.7 of Pruppacher & Klett, 1997) and dissolved solutes depress freezing temperatures further.

SLW drops have been reported in situ near the homogeneous freezing temperature in cirrostratus (Sassen, Liou, Kinne, & Griffin, 1985), orographic wave clouds (Heymsfield & Miloshevich, 1993), and in deep convective clouds (Rosenfeld & Woodley, 2000). In the latter study, droplet median volume diameter increased with height to about 17 μm at a temperature of -37.5°C, disappearing at colder temperatures as a result of homogeneous freezing. Rosenfeld, Woodley, Krauss, & Makitov (2006) sampled nearly adiabatic liquid water contents in intense, deep convection over Argentina and reported water droplets within the strongest updraft at -38°C. Droplet effective diameters were about 20 μm at those levels. Precipitation-sized droplets larger than 100 μm were not detected in those extremely supercooled conditions.

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Droplets commonly freeze at warmer temperatures via heterogeneous nucleation triggered by ice freezing nuclei (IFN), either internal to the droplets or through collisions with aerosol. Heterogeneous nucleation can also be caused by collisions with ice particles. Complete glaciation of supercooled clouds can occur through the Bergeron process, in which updrafts are not strong enough to maintain supersaturation with respect to liquid and droplets evaporate while vapor deposits on ice crystals (cf. Korolev, 2008). Glaciation in stronger updrafts is thought to require ice multiplication processes, such as ice splinter production when rime accretes supercooled drops in a narrow temperature range, or drop shattering during freezing (see, e.g., Fridlind et al., 2007; Ackerman et al., 2015, and references therein). Thus, factors that favor large amounts of SLW are intense convection and a dearth of IFN.

Supercooled water clouds present a well-known aviation hazard by causing airframe icing (Cober & Isaac, 2012; Cober, Strapp, & Isaac, 2001; Politovich, 1989), which can affect aerodynamic lift, aircraft weight, and external sensors of the aircraft. Icing effects strongly depend on the size of the SLW drops, which are classified in the literature as either small or large relative to a diameter threshold (varying between 30 and 100 μm depending on study). Supercooled large drops are also referred to by Rosenfeld et al. (2013) as either freezing drizzle (drop diameter between 200 and 500 μm) or rain (drop diameter larger than 500 μm). Politovich (1989) found that only 10 to 15 min of exposure to low concentrations of supercooled large drops led to substantial loss in aircraft climb capability. The lowest temperatures (-19°C (Ikeda, Rasmussen, Hall, & Thompson, 2007) and -21°C (Cober et al., 2001)) at which such large droplets are typically reported are substantially warmer than the homogeneous freezing limit, implying the presence of IFN and slow updrafts or active ice multiplication processes.

Interest in SLW and mixed-phase clouds has been driven by their contribution to uncertainties of climate projections resulting from cloud feedbacks poleward of 45° latitude, particularly over the Southern Ocean, where SLW is common in low-lying clouds. In a warming climate the transition from ice- to liquid-dominated clouds results in increased cloud albedo, which represents a negative cloud-climate feedback. A number of recent studies (see, e.g., McCoy, Hartmann, Zelinka, Ceppi, & Grosvenor, 2015, and references therein) have found that climate sensitivity in general circulation models depends on the partitioning between liquid and ice, largely because model differences in such partitioning impact the cloud feedback in the Southern Ocean.

In changing climate, satellite remote sensing is the only means for monitoring the evolution of cloud phase in real time and on a global basis. Therefore, development of remote sensing instrumentation and retrieval techniques capable of such monitoring is required. Field experiments contribute to this development in two main ways: by testing airborne prototypes of future satellite instruments as well as new retrieval algorithms, and, by providing validation datasets for existing satellite missions. In this study we report results from two such field campaigns.

2. Optical methods for cloud phase determination

One of the optical parameters that can be used to infer the cloud phase is the lidar volume depolarization ratio (VDR). Yorks, Hlavka, Hart, & McGill (2011a) studied the relationship between VDR and cloud phase statistically using NASA's Cloud Physics Lidar (CPL) (McGill et al., 2002) measurements made during five field experiments conducted over the continental United States and Hawaii in 2003–2007. Their analysis concludes that the clouds with VDR below 0.16 should be classified as liquid water clouds, while those with VDR above 0.27 should be attributed to ice clouds. The clouds with VDRs between 0.16 and 0.27 are considered to have complex cloud phases, i.e., to be mixtures of liquid water and ice. This study also found strong correlation of VDR with cloud temperature and height (with transitions from liquid to ice at around -20°C corresponding to 8 km). It should be noted that specular reflection on oriented ice crystals also leads to low depolarization ratios (Noel & Sassen, 2005; Zhou, Yang, Dessler, Hu, & Baum, 2012) and clouds containing oriented ice can be misidentified as liquid. This issue was addressed by another lidar-based cloud phase discrimination algorithm developed by Hu et al. (2009) for the Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP) instrument onboard the NASA Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite (Winker et al., 2009; Winker et al., 2010). Rather than depending primarily on depolarization ratios, this method differentiates cloud phases by using the spatial correlation of attenuated backscatter and particulate depolarization ratio. The advantage of this approach is its ability to separate the signatures of water clouds from those of ice clouds composed of randomly or horizontally oriented particles.

A global climatology of SLW clouds has been compiled by Hu et al. (2010) based on the above described analysis of CALIOP data combined with the measurements of cloud temperature from the Imaging Infrared Radiometer (IIR, also on CALIPSO satellite) and of cloud water paths from Moderate Resolution Imaging Spectroradiometer (MODIS, on the Aqua satellite). That study found that SLW clouds are mostly observed over ocean near the stormtrack regions (such as the Southern Ocean, (cf. Chubb, Jensen, Siems, & Manton, 2013)) and at high latitudes, where they constitute >95% of low-level cloud population. SLW clouds were also observed in the Northern Hemisphere over Europe, East Asia, and North America. The continental clouds showed higher liquid water content (LWC) than those over ocean. Choi, Lindzen, Ho, & Kim (2010) in another CALIOP-based study found that the global average fraction of supercooled clouds in the total cloud population is about 50% at -20°C isotherm and decreases towards lower temperatures. They also report anti-correlation between the SLW cloud fraction and the relative frequency of dust occurrence at the same isotherm that is especially pronounced in Asia. This finding is expected since dust particles can serve as glaciation nuclei (see e.g., (Sassen, DeMott, Prospero, & Poellot, 2003). Other types of glaciation nuclei include forest fire smoke (Sassen & Khvorostyanov, 2008), metallic particles of anthropogenic origin, sulfate aerosols, organic pollutants, and soil humic acids (DeMott et al., 2003; Knopf & Alpert, 2013).

Another approach to cloud phase determination is based on the difference in IR absorption properties between liquid and ice particles. Baum et al. (2000) applied a trispectral algorithm using 8.5-, 11-, and 12-μm bands to MODIS airborne simulator (MAS) measurements inferring cloud thermodynamic phase. In a more recent study Miller, Noh, & Heidinger (2014) presented another method that uses reflected sunlight in narrow bands at 1.6 and 2.25 μm to probe liquid-topped mixed-phase clouds.

Cloud thermodynamic phase can also be determined using polarimetric measurements of the relative magnitude of the primary rainbow feature in polarized reflectance occurring around 140° scattering angle. This approach is based on the fact that the rainbow can be produced only by spherical particles, i.e., by liquid droplets, but not by ice crystals, which are generally non-spherical or opaque. (Goloub, Herman, Chepfer, Riedi, & Brogniez (2000) and van Diedenhoven, Fridlind, Ackerman, & Cairns (2012b) developed cloud phase discrimination algorithm for Polarization and Directionality of the Earth's Reflectances (POLDER) satellite measurements. There was also an attempt to design a phase-detection algorithm for ground-based sky radiometers with polarimetric capabilities (Knobelspiesse et al., 2015).

3. NASA field experiments

Supercooled water and mixed-phase clouds were extensively observed during two recent NASA field campaigns: the POlarimeter Definition EXperiment (PODEX) and Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys (SEAC^{4}RS). These field experiments provided opportunities to observe SLW clouds from the high-altitude airborne platform of NASA's ER-2 aircraft. PODEX was sponsored by NASA's Aerosol-Cloud-Ecosystem (ACE) satellite mission (http://dsm.gsfc.nasa.gov/ace/), and was conducted