Near-Real-Time Satellite Cloud Products for Icing Detection and Aviation Weather over the USA

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ABSTRACT

A set of physically based retrieval algorithms has been developed to derive from multispectral satellite imagery a variety of cloud properties that can be used to diagnose icing conditions when upper-level clouds are absent. The algorithms are being applied in near-real time to the Geostationary Operational Environmental Satellite (*GOES*) data over Florida, the Southern Great Plains, and the midwestern USA. The products are available in image and digital formats on the world-wide web. The analysis system is being upgraded to analyze *GOES* data over the CONUS. Validation, 24-hour processing, and operational issues are discussed.

INTRODUCTION

Locations of aircraft icing conditions are currently available to pilots as a result of forecast model predictions or from pilot reports (PIREPS). These diagnoses are generally valuable but leave much room for improvement because of forecast errors or because of the age and sparse distribution of PIREPS. It has been recognized for many years that *GOES* data might be used to increase the spatial coverage and timeliness of icing reports because, the satellite imager provides direct information on cloud temperature [1] and some indication of cloud phase form the 3.9-μm channel [2]. The interpretation of the radiances is complicated by the angular dependence of the reflected intensities and ambiguity between ice and liquid water in some conditions. Thus, further advancement in satellite icing detection requires a more quantitative analyses of the satellite-observed radiances.

With the need for better understanding of the role of clouds in climate, physically based algorithms have been developed to retrieve cloud microphysical properties from polar orbiting satellites for climate research, in particular, the NASA Clouds and the Earth's Radiant Energy System Project [3]. The same algorithms are also applicable to the *GOES* imager data and have been used for near-real-time analysis over the Atmospheric Radiation Measurement (ARM) southern Great Plains (SGP) domain [4]. Because the retrieved cloud products include the cloud phase, temperature *Tc*, droplet effective radius *re*, and liquid water path *LWP*, they should be valuable for diagnosing icing conditions, which require the presence of supercooled liquid water SLW, larger droplets, and large liquid water content *LWC*. Smith et al. [5,6] showed that the *GOES* analysis yielded SLW in 98% of the available positive icing PIREPS for a variety of viewing and illumination conditions, demonstrating the excellent potential for the physical retrieval approach. Efforts to better quantify icing conditions from the *GOES* retrievals are continuing [7]. For effective use by the USA air traffic system, it is necessary to have near-real time data available over the entire contiguous USA (CONUS). This paper describes the development of an expansion of the currently limited *GOES* processing to include the CONUS in parallel with the efforts to quantitatively relate the retrieved cloud properties to objective measures of icing.

DATA & METHODOLOGY

The primary datasets for the retrievals include half-hourly GOES-8, 10, and 12 4-km spectral radiances. The GOES-8 and 10 imagers measure radiances at 0.65, 3.9, 10.8, and 12 μm, while GOES-12 uses a 13.3-μm channel in place of the 12-μm channel. GOES-12 has recently replaced GOES-8 at the eastern longitude, 75°W; GOES-10 remains at 135°W. The visible (VIS, 0.65 μm) reflectances are calibrated using the method [8]. Hourly Rapid Update Cycle (RUC) analyses [9] provide profiles of temperature and humidity for assigning height from *Tc* and for correcting the radiances for atmospheric attenuation. Clear-sky VIS reflectance for each location is derived form the CERES clear-sky albedo available on a 10' grid [10]. Spectral surface emissivity derived from GOES [11] and CERES [12] data are used with the RUC data to specify the clear-sky radiating temperatures at 3.9, 10.8, and 12-μm. The data are ingested and analyzed within ~15 minutes of the satellite observation.

The visible infrared solar-infrared split-window technique (VISST), an updated version of the 3-channel daytime method [3], is used during daytime, defined as the time when the solar zenith angle *SZA* is less than 82°. It matches the observed values with theoretical model s of cloud reflectance and emittance from radiative transfer calculations [13,14]. At night, the solar-infrared infrared split-window technique (SIST) is used to retrieve all of the cloud properties. The SIST, an improved version of the 3-channel nighttime method [3], uses thermal infrared data only. For each pixel, the methods retrieve *Tc*, cloud height *z* and thickness *h*, phase, optical depth τ, *re* or effective ice crystal diameter *De*, and LWP or ice water path *IWP*. SLW clouds are those pixels with $Tc <$ 273 K and a phase of liquid water. Other properties related to icing include *h*, τ, and *LWP*.

RESULTS

The GOES-8 data have been analyzed continuously over the ARM SGP since March 2000. Figure 1 shows an example of the GOES-8 images and cloud products derived over the ARM SGP at 1815 UTC, 3 March 2000. The brightest clouds occur over the southeastern portion of the cyclonic cloud system, while colder, higher clouds are evident over the northern and east central part of the system. The cloud mask shows the areas identified as clear or covered by ice, warm water or SLW clouds. Most of the SLW clouds have values of *Tc* between 265 and 273 K. Colder SLW clouds appear to have some thin cirrus clouds above them causing the clouds to appear colder than the lower cloud deck by itself. The values of *re* primarily range between 6 and 12 μm with some values as large as 15 μm. Some of the larger values arise from cirrus contamination while others are probably realistic and may correspond to areas with drizzle or very large droplets. Optical depths are quite large over most of the lower-cloud areas. The most likely SLW areas with icing conditions most likely correspond to large values of τ, *re*, and *LWP*. *LWP* is greatest over central Missouri and western Arkansas, where icing was reported from PIREPS [5].

Continuous monitoring of clouds over the Midwest began during January 2003 to coincide with ongoing icing research. Icing test flights were performed west of Cleveland, Ohio during the afternoon of 18 February 2003. Figure 2 shows that LWP exceeded 400 gm^{-2} and $re > 15$ μm in the area where the NASA Glenn Twin Otter reported large LWC and clear to mixed icing (Cory Wolff, personal communication). Most of the low clouds over the entire Midwest are composed of SLW with *Tc* between 260 and 270 K. Clouds with large *re* occur in large clumps and are generally consistent with areas with large *LWP*. Some of the large *re* values are evidently caused by the presence of thin cirrus over the lower cloud deck. The icing flight on this day occurred in clouds around 1 km, while *z* is around 3 km in Fig. 3. The in situ temperature of –9°C is close to the value of *Tc* in the flight area. Thus, the error in *z* is a result of the temperature profile used to convert *Tc* to *z*. Sharp boundary-layer inversions are difficult to characterize in weather analyses and are often hard to measure with enough precision to obtain the cloud-top temperature [15]. Much of the low cloud cover occurred over snow-covered land causing misclassification of the some of the clouds. Earlier validation studies indicate that, except for the cloud height under low-level inversions, the derived cloud properties are very close to those from objective, independent measurements of the same quantities [16, 17].

Until the start of GOES-12 operations in early April 2003, cloud properties were being analyzed in near-real time over the Midwest, the ARM SGP and Florida. The domains for these areas are outlined as grids in Fig. 3. Also shown are the domains for analyzing data from GOES-12 (East) and GOES-10 (West). The CONUS domain will be divided at 105°W between the two satellites. Building on the current data ingest and analysis systems, data from each satellite will be processed for all ocean and land areas between 25°N and 50°N. The western half of the domain will extend to 135°W, while the eastern half will start at 65°W. Initial processing will use hourly data and should be underway by late summer 2003.

DISCUSSION AND CONCLUDING REMARKS

Although the preliminary results are encouraging, much additional refinement is needed prior to any operational implementation of the algorithms. The relationships between the derived cloud properties and icing conditions must be established to within some tolerable uncertainties through aircraft-satellite comparisons [7]. Logic must be developed to account for upper-level cloud obscuration of the lower-level SLW clouds. Because aircraft altitude is an important consideration, the errors in *z* derived from *Tc* must be reduced. One approach that has worked well over ocean boundary-layer clouds [15] is the use of a lapse-rate in place of the RUC profile in the boundary layer [18]. A fixed lapse rate is anchored to the surface temperature and used to describe the vertical temperature profile until it meets the RUC profile or up to 700 hPa. Between 500 and 700 hPa, the lapse rate is adjusted until it converges with the RUC profile at 500 hPa. Over land, the diurnal range in the surface temperature *Ts* precludes using an instantaneous value of *Ts* to anchor the lapse rate. A 24-hr running average value of *Ts* may eliminate the diurnal effect and yield a reasonable profile.

Figure 4 shows an example of the 1500 UTC 4 April 2000 profile from the European Center for Medium rand Weather Forecasting (ECMWF) analysis for the ARM SGP site in north-central Oklahoma. It shows a distinct inversion at 860 hPa and $T = 273$ K. Because $Tc = 271$ K, the satellite retrieval places the cloud top at $z = 3.7$ km (650 hPa). The ARM radar image (available from http://www.met.utah.edu/mace/homepages/research/ar chive/sgp/sgp.html) shows that the actual cloud top is near 1.7 km confirming a 2-km cloud-top height overestimate. The lapse rate method, while not providing a realistic characterization of the inversion, produces the correct cloud height and could be useful for adjusting the analysis profile. Similar results are obtained using the RUC profiles.

Since air traffic operates 24 hours per day, it is desirable to develop an icing detection system that operates in all illumination conditions. The SIST produces the same the same cloud properties as the VISST, but the *LWP* is meaningful only for clouds with $\tau < 20$ or so because of the limitations of infrared emission. Thus, much additional research is required to provide icing related parameters at night. In low sun conditions (SZA > 82°), the information in the 3.9-μm channel, crucial for phase determination and particle size retrieval, is compromised because the reflected portion of the radiance is too small to interpret. Other spectral channels may be needed to monitor cloud properties in that situation.

Another major consideration is the new channel , 13.3 μm, on the newest GOES series. The 12-μm channel provides valuable information about phase and thin clouds, especially at night. The information content of the 13.3-μm radiance will need to be determined and utilized, hopefully in a similar manner.

The foundation for an operational near-real time cloud analysis system is well established. The cloud products appear to be valuable for diagnosing icing conditions. Development of a prototype near-real time icing product is underway based on the preliminary studies. The initial results for at least one of the GOES satellites will be made available later this year for validation, further research, and improvement.

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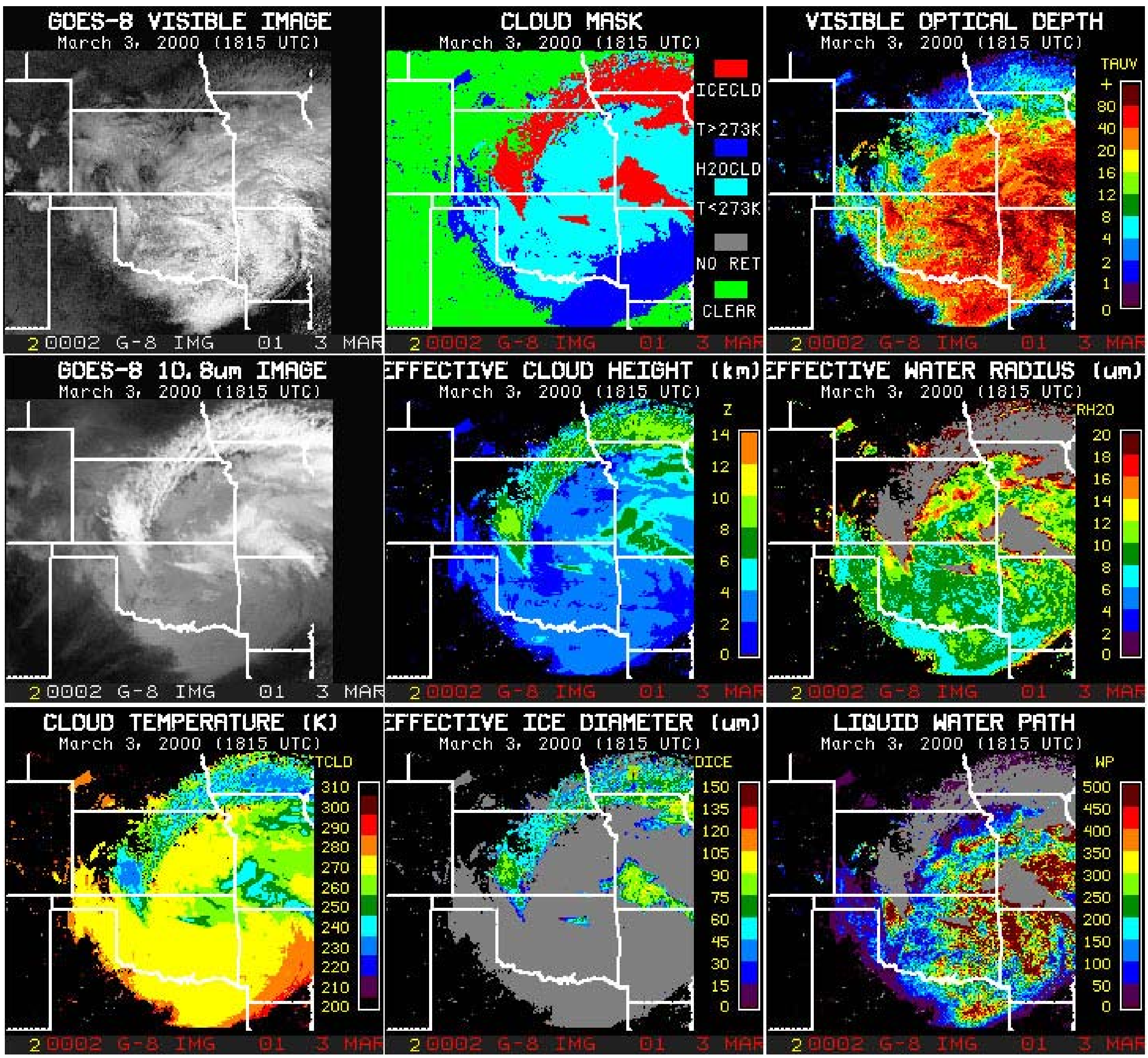

Fig. 1. GOES-8 visible and infrared imagery and derived cloud properties at 1815 UTC, 3 March 2000 over ARM southern Great Plains domain.

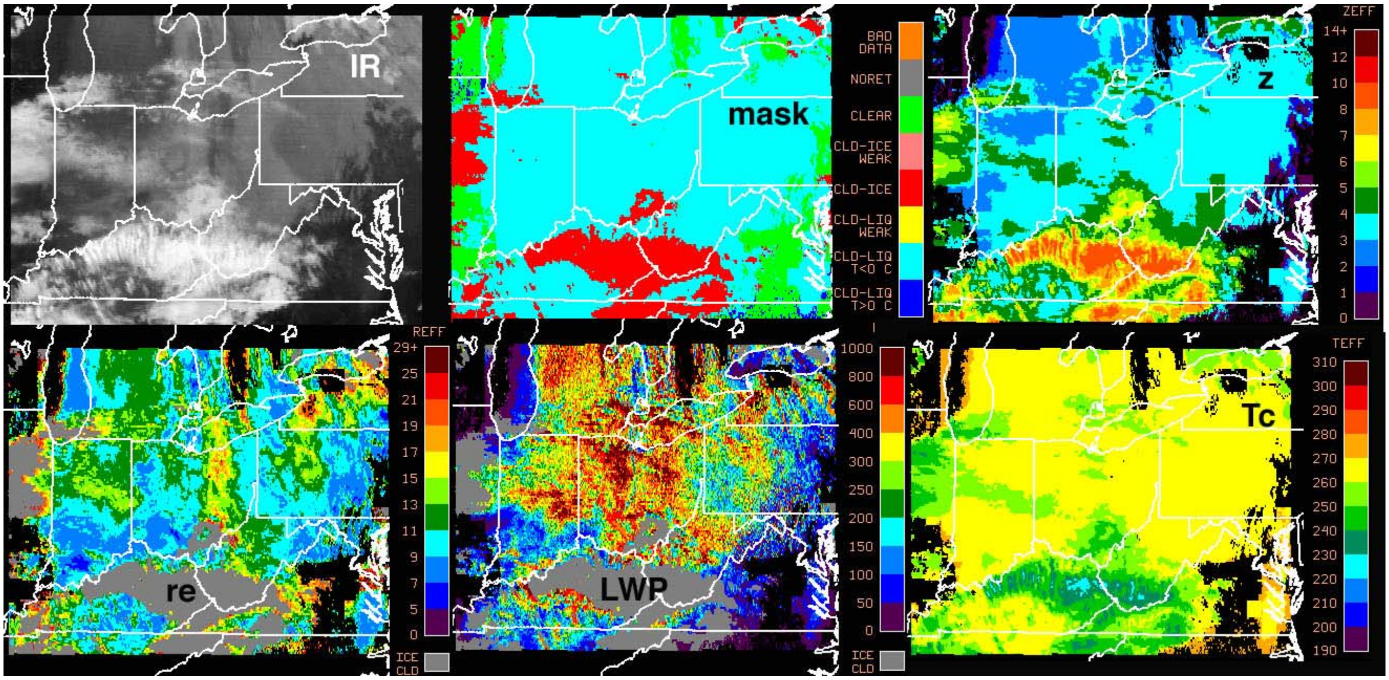

Fig. 2. GOES-8 visible and infrared imagery and derived cloud properties at 2045 UTC, 18 February 2003 over Midwestern USA domain.

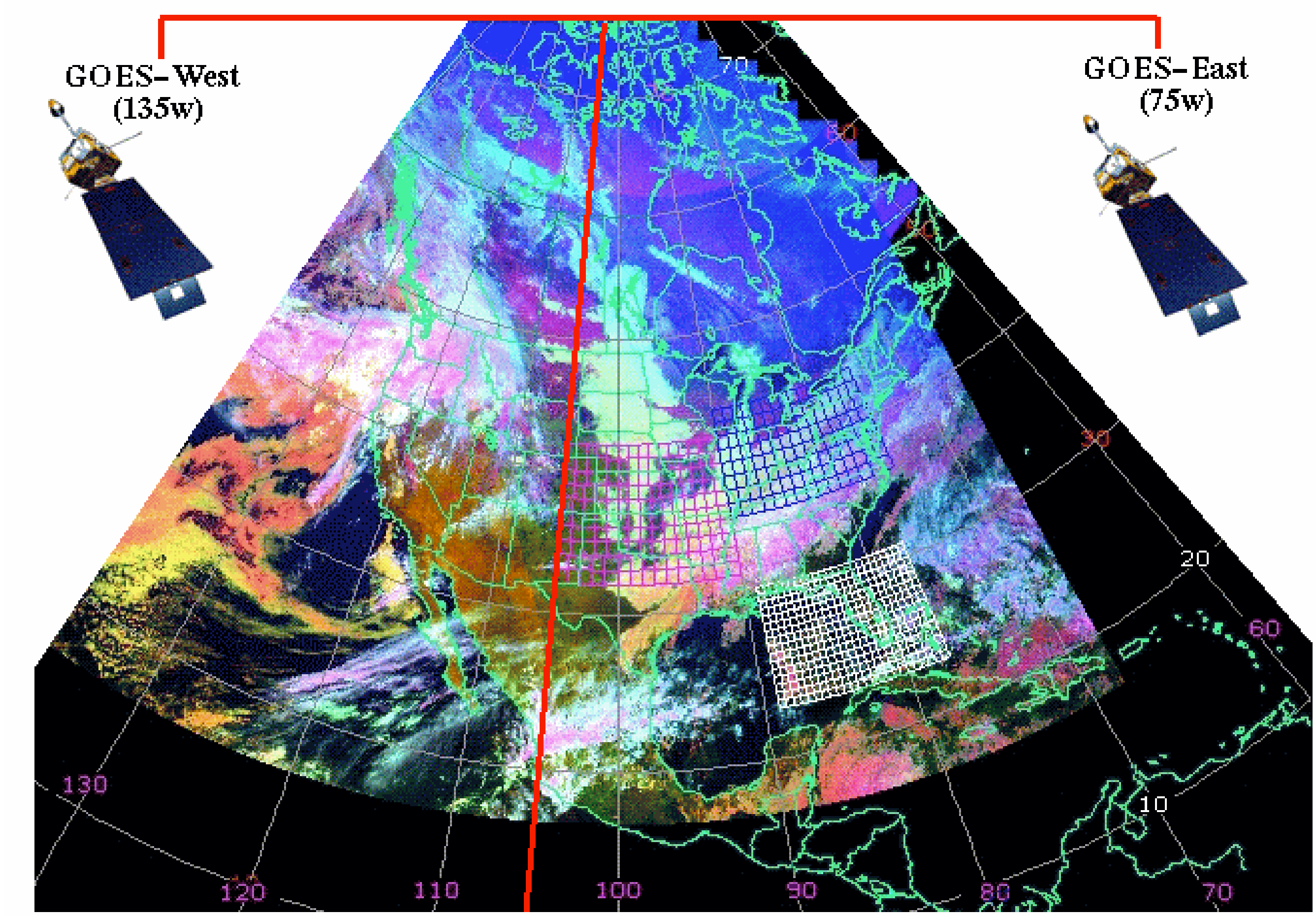

Fig. 3. CONUS domain for near-real time cloud products (25°N – 50°N; 65°W – 135°W) and coverage by GEOS-East and GOES-West. ARM, Midwestern, and Florida domains currently analyzed are shown as grids.

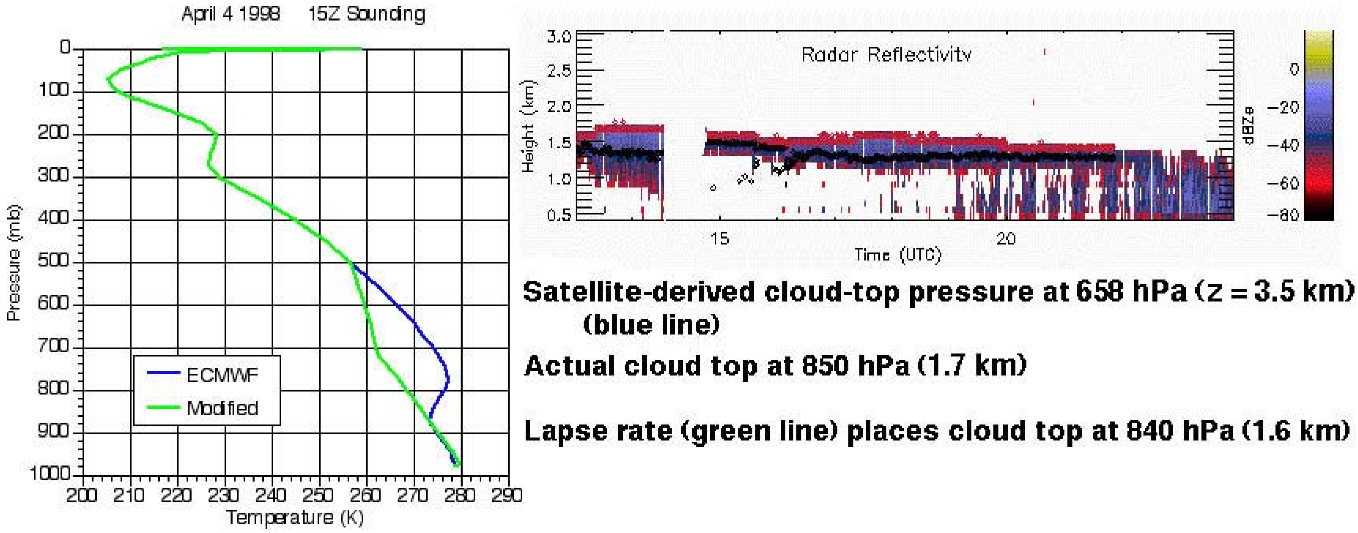

Fig. 4. ECMWF sounding (blue line) and lapse rate sounding (green) over ARM SGP site, 1500 UTC, 4 April 2000. The surface-based radar image of the cloud deck between 1500 and 2400 UTC.