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Study of thin clouds at CNR-IMAA Atmospheric Observatory (CIAO)

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I. INTRODUCTION

Space-based measurements allow us to study atmospheric variables at global scale, but ground-based observations are necessary for calibration and validation [GCOS, 2006]. Upcoming satellite missions aim at showing the benefit coming from the availability of technological improvements and innovations. However, research is necessary to improve retrieval algorithms of atmospheric variables and to assess the real advances in the knowledge of weather and climate. Quality-controlled vertical profiles of atmospheric key variables provided by ground-based advanced atmospheric observatories represent the optimal basis for the satellite cal/ val programs. So far, atmospheric observatories are working towards the development of new observation strategies and the full exploitation of the synergy among active and passive profiling sensors. This is highly relevant for the new generation satellites equipped with multiple sensors on board the same observation platform.

Ground-based observations provide long-term monitoring of parameters that, at present, cannot be monitored from space observations. For instance, the study of thin liquid water clouds as well as the mechanisms leading to droplet activation is challenging for satellite passive sensors, whereas they are important for weather and climate studies.

The impact of thin clouds on climate is highly uncertain. Thin liquid water clouds, which are low or midlevel super-cooled clouds characterized by a liquid water path (LWP) less than 100 g m^{-2}, are difficult to be observed accurately and large discrepancies exist among different observation techniques [Turner et al., 2007]. The importance of these clouds is related to their extensive global mean coverage: low and midlevel clouds, often containing liquid water, are characterized by a mean LWP value of 51 and 60 g m^{-2}, and cover 27.5% and 19% of the global surface, respectively, while the global mean cloud coverage is 68.6% [Rossow and Shiffer, 1999].

Ground-based profiling techniques, such as advanced multi-wavelength lidar and Doppler radar techniques, allow us to study aerosol and cloud microphysics; they can be considered as the needed bridge between in-situ and satellite measurements to fill in the gaps in the understanding of the physical mechanisms leading to cloud formation.

In this work, two examples of possible solutions towards the improvement of the accuracy in the estimation of thin cloud properties are proposed. The study is based on the multi-wavelength lidar, Doppler radar and microwave radiometer measurements performed at

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the CNR-IMAA Atmospheric Observatory (CIAO). The observatory is located in Potenza, Southern Italy, on the Apennine Mountains (40.60N, 15.72E, 760 m a.s.l.), less than 150 km from the West, South and East coasts [Madonna et al., 2011]. The first example addresses the enhancement of Doppler radar sensitivity achieved adopting a spectra averaging over the time, with the aim to detect tiny droplets, as those forming fog or thin clouds. In the second example, particular attention has been paid to an optically thin broken stratocumulus cloud that gives us the opportunity to investigate the differences between non-saturation and saturation conditions in an aerosol layer and the droplet activation mechanisms, using Raman lidar measurements.

II. THIN CLOUDS: RADAR SENSITIVITY

Sensitivity of millimeter-wavelength Doppler radars allows to study microphysical properties of non-precipitating clouds. These radars provide accurate reflectivity measurements over a dynamic range of approximately seven orders of magnitude, from -50 dBZ to +20 dBZ throughout the troposphere [Kollias et al., 2001]. A large fraction of clouds is composed of high concentrations of small hydrometeors with diameters from a few to tens of micrometers, with reflectivity values from -60 dBZ to –40 dBZ [Kollias et al., 2001]. When the reflectivity of the small hydrometeors is very weak (less than -50 dBZ), these targets fall outside the radar detectable range.

The primary measurement provided by Doppler radars is the Doppler spectrum. Typically, the first three moments of the radar Doppler spectrum are provided and used in radar data analysis: the signal-to-noise ratio (SNR – zeroth moment), the mean Doppler velocity (first moment) and the Doppler spectrum width (second moment). For systems operating in zenith pointing mode, the typical time resolution of a single radar vertical profile is of the order of seconds, while the typical vertical resolution is of a few tens of meters.

In order to increase the radar sensitivity, the spectra pre-processing of radar measurements performed at CIAO station is performed using two different options: (1) “routine” pre-processing, based on averaging 200 spectra with a vertical resolution of 30 m and a time resolution of 10 s; (2) “averaging” pre-processing, based on averaging 3600 spectra (averaging the spectra over 3 range gates and 1 minute) with a vertical resolution of 90 m and a time resolution of 1 minute. The second option allows us to enhance the radar sensitivity of 5-10 dBZ, up to about -55 dBZ.

Figure 1 shows the temporal evolution of radar reflectivity factor Ze in the “routine” pre-processing option (panel a) and in the “averaging” option (panel b), and the linear depolarization ratio (LDR) in the “averaging” option (panel c), measured on 10 October 2011 by radar at CIAO. All these time series are clutter filtered. The clutter filtering is carried out after the estimation of the noise level in the radar power spectrum [Bauer-Pfundstein, 2007]. In figure 1a, the black line shows the height of the melting layer retrieved using surface measurements of temperature and the modeled temperature profiles of a standard atmosphere. In both processing options, Ze indicates the presence of ice cloud at around 7 km above sea level (a.s.l.) at 13:00 UT and low-level liquid water clouds below 3 km a.s.l., alternated with occasional rain showers. Moreover, liquid water layers are detected up about 2 km a.s.l. between 00:00 and 04:00 UT and between 17:00 and 20:00 UT, only using the “averaging” pre-processing option (figure 1b). This is due to the tiny size of the droplets of these layers, likely fog, whose liquid phase is confirmed by the absence of signature in the LDR (figure 1c). The discussed case shows how the averaging of radar spectra over larger vertical and temporal domains allows the radar to extend its own sensitivity: this is highly relevant in the study of thin clouds and fog. An enhanced radar sensitivity allows us to extend the size range of hydrometeors detected by the radar as well as to contribute to a better exploitation

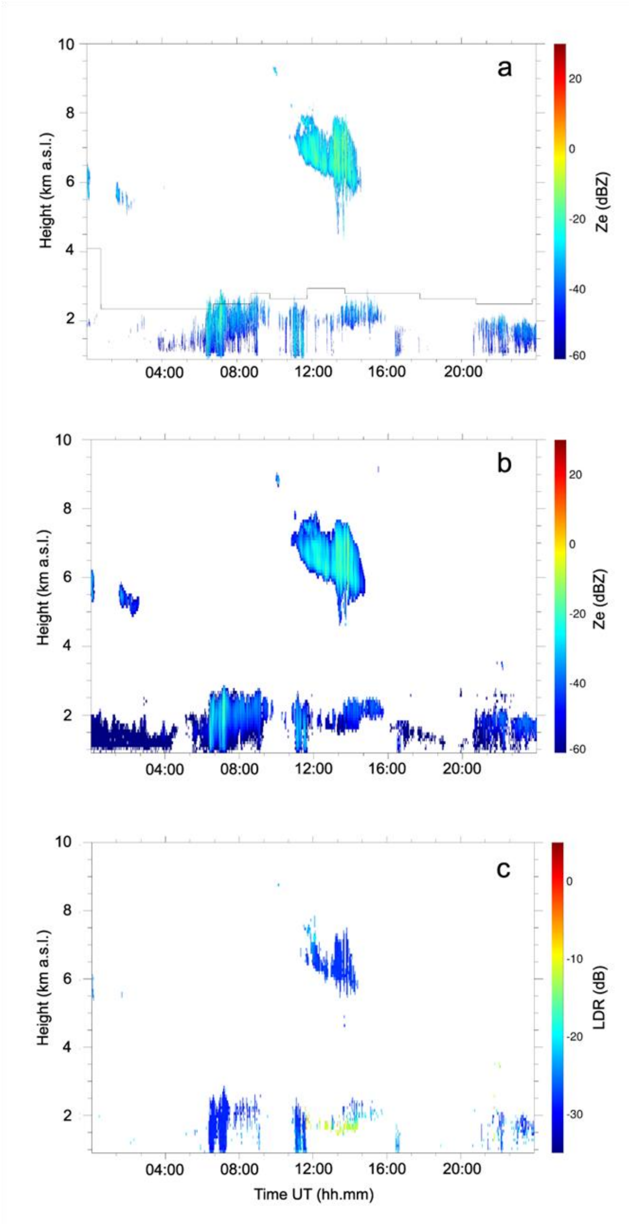

Figure 1: (a) Time series of vertical profiles of clutter filtered radar Reflectivity Factor (Ze) measured on 10 October 2011 at CIAO using the “routine” processing (time resolution is 10 seconds and vertical resolution is 30 meters), black line indicates the melting layer height; (b) same as reported in panel (a) but using the “averaging” processing (time resolution is 1 minute and vertical resolution is 90 meters); (c) time series of vertical profiles of clutter filtered radar Linear Depolarization Ratio (LDR) for the same date, obtained using the “averaging” processing.

of instrument synergies. The study of aerosol, water vapor and liquid water in thin clouds can also be considered as a good opportunity for the quantification of the aerosol indirect effect. This work is currently ongoing at CIAO along with the evaluation of downdrafts and updrafts observed with the Doppler radar.

III. THIN CLOUDS: RAMAN LIDAR AND DROPLET ACTIVATION

Aerosol particles may be activated into droplets when super-saturation conditions are reached in a rising air mass. Cloud droplet activation is a highly complex and nonlinear process: only a fraction of particles can grow beyond the critical sizes to form droplets, depending on several factors such as size distribution, chemical composition and updraft velocity [Ming et al., 2006].

From the ground based remote sensing point of view, the possibility of investigating this process is related to the capability of the instruments to provide accurate estimation of aerosol and clouds properties. Thin clouds are one of the possible targets that allow us to study these processes. Though thin liquid water clouds are difficult to be observed accurately and large discrepancies exist among different observation techniques [Turner et al., 2007], they are effectively observed through ground-based remote sensing rather than through passive satellite remote sensing. At CIAO, two multi-wavelength Raman lidars, PEARL (Potenza EArlinet Raman Lidar) and MUSA (Multi-wavelength System for Aerosol), are operational [Madonna et al., 2011]. Both systems emit light pulses at 355, 532 and 1064 nm and detect the elastically backscattered radiation by atmospheric constituents and the Raman backscattered radiation by nitrogen molecules at 387 and 607 nm, and by water vapor molecules at 407 nm, the last only for the PEARL system. Vertical profiles of aerosol optical properties and water vapor mixing ratio are retrieved from lidar signals acquired with a raw vertical resolution of 15 m (7.5 m for 1064 nm) for PEARL and 3.75 m for MUSA, and a raw time resolution of 60 seconds.

Figure 2a shows the temporal evolution of the lidar range-corrected signal at 1064 nm measured by MUSA on 4 August 2011 from 19:22 to 21:16 UT. The plot shows the presence of broken clouds between 3 and 4.5 km of altitude a.s.l. The observation of broken clouds gives us the opportunity to calculate the vertical profiles of aerosol optical properties and water vapor content in twofold manner: “with clouds”, by averaging all lidar signals, and “without clouds”, by skipping the signals showing the presence of clouds. The number of skipped signals in the profiles “without clouds” is expressed through the so-called skipped fraction, defined as the number of skipped signals divided by the total number of signals. The cloud contaminated lidar returns have been identified by visual inspection and assuming that a strong negative slope in the nitrogen Raman lidar signals at 387 nm corresponds to the presence of liquid water droplets. This cloud detection technique has been used preliminarily in order to verify the reliability of all the profiles containing clouds. However, the procedure can be automated, and this will be done in the near future through the use of the EARLINET Single Calculus Chain (SCC) for the automatic retrieval of the aerosol optical properties starting from raw lidar signals [D’Amico et al., 2012].

Figure 2b shows the vertical profiles of aerosol extinction coefficient at 355nm “with clouds” (red line) and “without clouds” (black line) obtained using Raman lidar technique, averaging lidar signals over the same time interval of 17 minutes, from 19:33 to 19:50 UT. Besides, figure 2c shows the vertical profiles of relative humidity “with clouds” (red line) and “without clouds” (black line) estimated with Raman lidar technique, averaging lidar signals from 19:33 to 19:50 UT, and calibrated with water vapor measurements performed by a co-located and simultaneous radio-sounding. In both figures 2b and 2c the profiles have an effective vertical resolution of 780 m and a skipped fraction of 0.29. Finally, in figures 2d and 2e the same as in figures 2b and 2c is reported, but averaging lidar signals over a time interval of 103 minutes, from 19:33 to 21:16 UT, with an effective vertical resolution

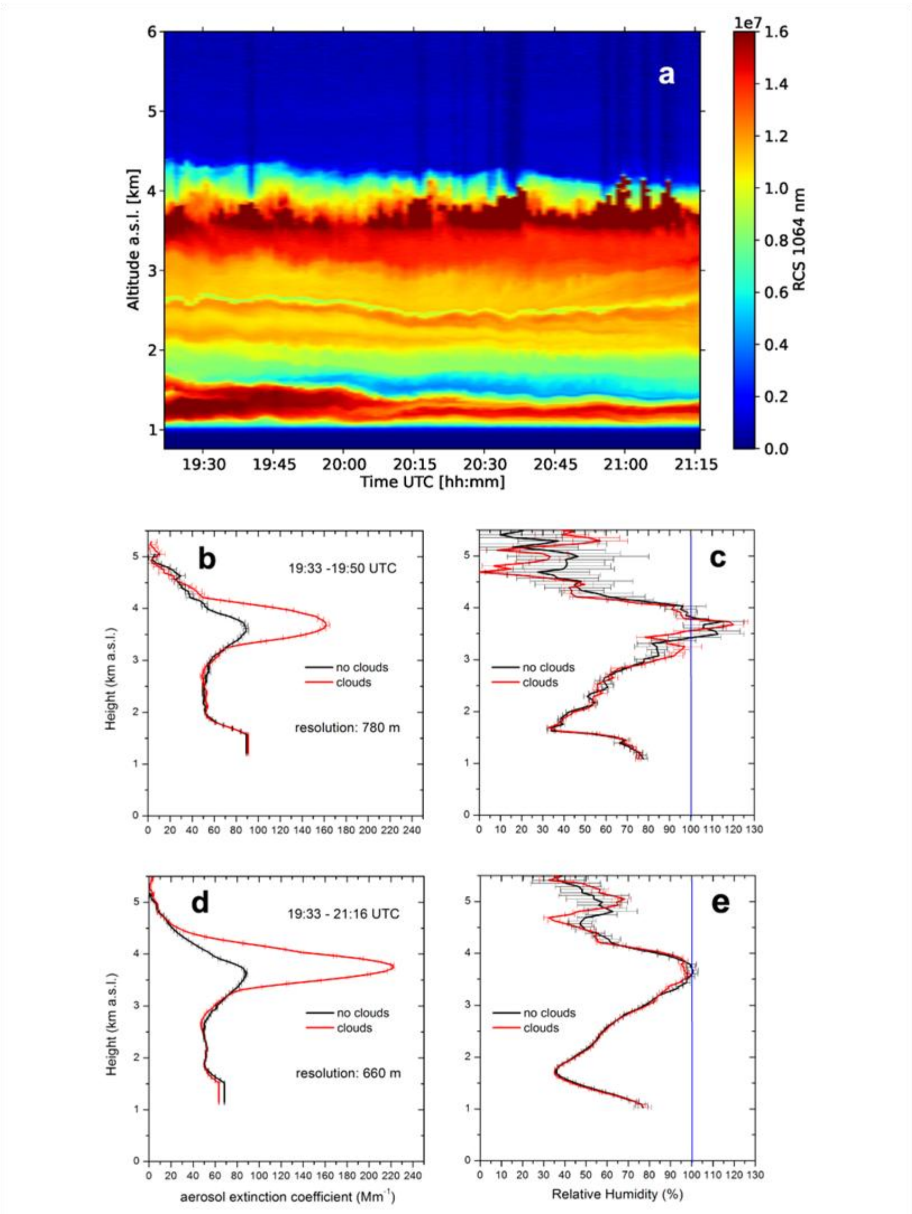

Figure 2: (a) Time series of range-corrected signal at 1064 nm obtained from MUSA on 4 August 2011 from 19:22 to 21:16 UT using a time resolution of 1 minute and a vertical resolution of 3.75 m; (b) vertical profiles of 355 nm aerosol extinction coefficient retrieved using lidar signals including clouds (“with clouds” - red line) and skipping clouds (“without clouds” - black line) and averaging the lidar signals over 17 minutes, from 19:33 to 19:50 UT; (c) vertical profiles of relative humidity “with clouds” and “without clouds”, corresponding to the profiles reported in panel (b), calibrated using a co-located and simultaneous radiosounding. In both (b) and (c) panels, the profiles have an effective vertical resolution of 780 m (skipped fraction = 0.29); (d) vertical profiles of 355 nm aerosol extinction coefficient retrieved using lidar signals including clouds (“with clouds” - red line) and skipping clouds (“without clouds” - black line) and averaging the lidar signals over 103 minutes, from 19:33 to 21:16 UT; (e) vertical profiles of relative humidity “with clouds” and “without clouds”, corresponding to the profiles reported in panel (d), calibrated using a co-located and simultaneous radiosounding. In both (d) and (e) all the profiles have an effective vertical resolution of 660 m (skipped fraction = 0.40).

of 660 m and a skipped fraction of 0.40. The error bars in the profiles of figures 2b and 2c are larger than those of figures 2d and 2e, because the smaller the time interval over which the lidar signals are averaged, the lower the signal to noise ratio.

In figures 2b and 2d, extinction coefficient profiles for both “with clouds” and “without clouds” cases are found to be in good agreement reaching an altitude of about 3.2 km a.s.l. This suggests that aerosol particles do not nucleate. In the region above, “with clouds” profiles (red lines) rise significantly compared to “without clouds” profiles (black lines) because of the aerosol activation and the droplet formation. From about 4.5 km a.s.l., the extinction profiles “with clouds” and “without clouds” are in good agreement again. Therefore, the layer extending from 3.2 km to 4.5 km a.s.l. can be considered as the region where aerosol particles are activated and droplets form. These results seem to be confirmed by the relative humidity profiles shown in figures 2c and 2e. Such profiles show a significant increase of relative humidity within the activation layer and a saturation condition reached in the middle part of the activation region where droplets form. The interpretation of such profiles needs further investigation.

The presented case study reveals the advantage of studying broken thin liquid water clouds, as they offer the possibility to characterize the aerosol activation region and to separate it from the region not affected by the activation process.

IV. Summary

Quality-controlled vertical profiles of atmospheric key variables provided by advanced atmospheric observatories, like CIAO, are highly relevant for definition and implementation of suitable strategies for calibration and validation for both geostationary (e.g. Metop) and polar orbiting (e.g. OMI, Terra/ Aqua, ADM-Aeolus and EarthCARE) satellite platforms. They allow us to study macrophysical and microphysical properties of aerosol and clouds over long term, including parameters challenging to be addressed with satellite observations.

Thin clouds represent one of the major source of uncertainty in the estimation of global radiative balance and in the characterization of aerosol-cloud interactions. Two examples relative to the use of Doppler radar and Raman lidar measurements have been discussed. The first stresses the need for using a suitable temporal and vertical averaging of radar spectra in order to increase the sensitivity of radar in the detection of small droplets, as those forming fog or thin clouds. The second describes the advantage of studying thin broken clouds, using Raman lidar measurements, to distinguish the regions where aerosol particles are activated or not. Complementary water vapor mixing ratio measurements with Raman lidar contribute to identify the droplet formation region. The presented methodology is currently under investigation over a large dataset of radar and lidar measurements collected at CIAO in the period 2009-2012. Study of thin liquid water clouds, as well as the related mechanism leading to droplet activation, is challenging using space observations only. Ground based lidar and radar observations can strongly contribute to improve satellite retrievals and to advise on the technological requirements for future satellite missions.

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