Synergetic application of a ground-based Raman lidar and an airborne spectrometer to study the evolution of a cirrus cloud

Paolo Di Girolamo[(1)], Tiziano Maestri[(2)], Rolando Rizzi[(2)], Donato Summa[(1)], Filomena Romano[(3)]

[(1)] DIFA, Università degli Studi della Basilicata, Viale dell'Ateneo Lucano n. 10, 85100 Potenza, Italy, Email: digirolamo@unibas.it
[(2)] Dip. di Fisica, Univ. di Bologna, viale Berti-Pichat 6/2, 40127 Bologna, Italy, Email: T.Maestri@.adgb.df.unibo.it
[(3)] IMAA – CNR, C.da S. Loja, 85050 Tito Scalo, Italy, Email: romano@imaa.cnr.it

ABSTRACT

A ground-based Raman lidar system (*BASIL*) is operational at DIFA-Università della Basilicata (Potenza, Southern Italy). The system was involved in a measurement campaign (5-10 September 2004) in the frame of EAQUATE, an international experiment for hyper-spectral atmospheric sounding validation. The experiment involved the NASA Proteus aircraft, equipped with the sensors NAST thermal infrared interferometer (NAST-I) and microwave radiometer (NAST-M), the Scanning HIS infrared interferometer (S-HIS), and a range of ground based and airborne remote sensing instruments.
On the evening of September 6, 2004, the Proteus aircraft flew four times over a moderately thick high cirrus cloud in the Potenza region. The evolution of the cirrus cloud was monitored by *BASIL,* providing measurements of particle backscatter and extinction, water vapour mixing ratio, atmospheric temperature and relative humidity. Information from three radiosondes launched from the IMAA ground station was also considered.
Radiance measurements by NAST-I are compared with accurate radiance simulations based on data from *BASIL* and the radiosondes. Based on the quality of the comparison among simulated and measured radiances, it has been possible to define the vertical structure in terms of fluxes and cooling/heating rates, thus providing a link between the measured state and the time evolution of the cirrus cloud. The effectiveness of the methodology has been also tested and verified on a clear sky case on September 8, 2004.

1. INTRODUCTION

Data analyzed in this work were collected during the first phase of the international field experiment campaign EAQUATE, which took place in Italy from 5 to 10 September 2004. A second phase of the experiment took place in the UK (13- 22 September 2004). The EAQUATE campaign was designed to study the atmosphere using aircraft and ground based instruments, demonstrating the benefit of these measurements in validating hyper-spectral satellite sounding observations. The Proteus high altitude aircraft participated in both campaigns, providing measurements with NAST-I, NAST-M, S-HIS, the FIRSC far-IR interferometer, and the micro-MAPS CO sensor.
Data analyzed in this paper refer to the second measurement day of the Italian campaign (6 September) when the Proteus aircraft flew four times over an high cirrus cloud in the Potenza region. High spectral resolution ($\Delta\nu$=0.25 cm^{-1}) measurements of the radiance field [-45, +45°] were collected during these overpasses by the NAST-I sensor covering the long-wave band region 645-2700 cm^{-1}. The cloud evolution was monitored by *BASIL* by measuring particle backscatter and extinction at 355 nm. *BASIL* also measured the water vapour mixing ratio and atmospheric temperature profiles, with accurate information of the statistical measurement uncertainty so that large uncertainties of the lidar-measured parameters could easily be identified and excluded from further interpretations. Three radiosondes were released from the IMAA ground station (Tito Scalo - Potenza) in 4 hours, these additional data contributing to acquire a very accurate description of the time evolution of the atmospheric temperature profile and of the atmospheric gaseous and particulate state.
The objectives of the study were: 1) to co-locate and jointly process data measured by a range of different sensors (Radiosondes/Raman-lidar/NAST-I interferometer) exploiting their potential synergies ; 2) to evaluate the relevance of the lidar information in clear and cloudy sky conditions; 3) to simulate NAST-I data at different viewing angles and investigate the consistency between measured and modelled radiances in presence of ice clouds; 4) to determine the temporal sequence of the cooling rate profiles and evaluate the importance of the combined lidar–spectrometer information in predicting the evolution of a cirrus cloud and 5) to set the basis for a study of the evolution of the cirrus cloud accounting for the dynamics and microphysics.

2. DATA ANALYSIS AND RESULTS

NPOESS Airborne Sounding Testbed-Interferometer (NAST-I) has a spectral resolution of 0.25 cm^{-1} and a spectral range of 3.6–16.1 µm, covering the spectral ranges of all planned advanced high spectral resolution infrared spectrometers to fly within the next decade on polar orbiting and geostationary weather satellites. Based on the above spectral specifications, NAST-I

provides a vertical resolution of 1–2 km for atmospheric temperature and water vapour.
The major feature of *BASIL* is its capability to perform high-resolution and accurate measurements of atmospheric temperature, both in daytime and night-time, based on the application of the rotational Raman lidar technique in the UV [1]. Besides temperature, *BASIL* is capable to provide measurements of particle backscatter at 355 and 532 nm, particle extinction at 355 nm, particle depolarization at 355 (implemented after the present field campaign) and water vapour mixing ratio. Relative humidity measurements are obtained from simultaneous water vapour and temperature measurements. Fig. 1 is a picture of *BASIL,* which the laser transmitter in the foreground and the receiver in the background.

Fig. 1: The lidar system *BASIL*.

Lidar measurements were acquired with a maximum temporal and vertical resolution of 1 min and 30 m, respectively. Vertical and temporal resolution can be traded-off to improve measurement precision. Typical precision at 2 km altitude for day-time measurements is 2 % for particle backscattering coefficient, 10 % for particle extinction coefficient, 10 % for water vapour mixing ratio and 2 K for temperature, while for night time measurements is 1 % for particle backscattering coefficient, 5 % for particle extinction coefficient, 2 % for water vapour mixing ratio and 1 K for temperature.
The radiosonde temperature profile is used to characterize the atmosphere below flight level during the 4 overpasses. The water vapour mixing ratio profile, obtained from the lidar measurements, is used when the associated percentage error is less than 50%, while radiosonde data are used to fill the lidar blind region (60 m above the lidar) and the lidar data affected by large uncertainties. As the simulated field is the one above the DIFA lidar ground station, lidar data are more appropriate in terms of time and location with respect to that obtained from radiosondes for the definition of the water vapour profile to be used in the simulations. The atmospheric column above the altitude region covered by lidar and radiosondes data is described using the US Standard (USS) atmospheric profile. The concentration profiles for the other molecules (CO_2, O_3, N_2O, CO, CH_4, O_2, NO, SO_2, NO_2 ,N_2, CCl_3F, CCl_2F and CCl_4) are also taken from the USS. The number of levels used for the computation is 94. The number of layers occupied by the cloud is variable and related with the actual cloud geometrical depth measured by the lidar.
The NAST-I radiances measured during the 4 overpasses and the Raman lidar data indicate the presence of an high cirrus cloud whose optical depth is decreasing from the first to the fourth overpass. Lidar backscatter data places cloud top at about 10 km of altitude above the DIFA site, as indicated in Table 1 that contains a summary of the main features of the cirrus cloud in correspondence to the 4 Proteus overpasses over Potenza. Figs. 2 and 3 show the evolution with time during the cirrus cloud episode of particle backscatter at 355 nm and specific humidity, respectively. The vertical stripes represent the Proteus overpasses.

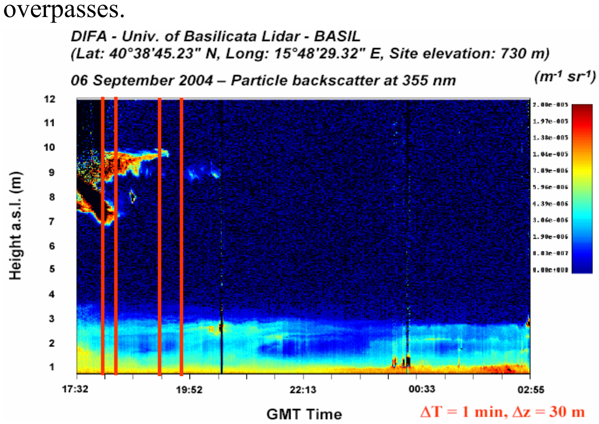

Fig. 2 Time evolution of particle backscattering coefficient at 355 nm during the cirrus cloud episode.

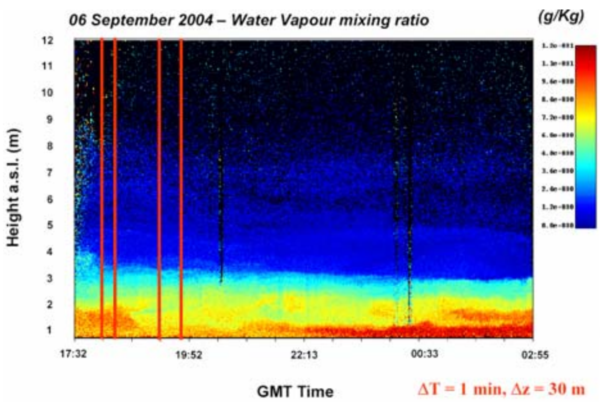

Fig. 3 Time evolution of specific humidity during the cirrus cloud episode.

The general evolution of the cloud field was also monitored using MSG infrared images, available every 15 minutes. Fig. 4 illustrates SEVIRI channel #9 [10.8 µm] image at 18 :27 UT on 6 September 2004, which is almost time-coincident with the 2nd Proteus overpass.

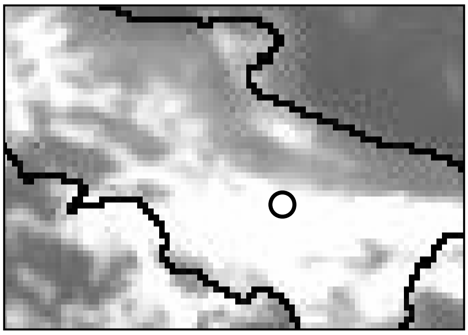

Fig. 4: SEVIRI channel #9 [10.8 µm] image at 18 :27 UT on 6 September 2004. Potenza is represented by the circle in the figure.

Line-by-line computations of molecular optical depths are performed using HARTCODE [2]. Single scattering properties for the cloud layers are generated assuming that ice particles are hexagonal columns [3,4]. The cloud optical depths, altitudes and geometrical thickness for the 4 overpasses are determined by the lidar measurements of extinction and backscattering coefficients. The radiative transfer calculations are based on the adding and doubling method to handle multiple scattering conditions [5,6] and the high spectral resolution radiances are convolved with the NAST-I instrument function.

Table 1: Main features of the cloud as measured by the DIFA Raman lidar

Overp # GMT hh:mm	Lowest cloud Limit [km]	Upper cloud Limit [km]	# of layers	Total Optical Depth at 355 nm Up/Down	Sim. IR Trans. 900 cm^{-1}
1 18:02	6.505	10.065	2	2.45 (1.44 / 1.01)	0.30
2 18:20	6.710	10.020	2	0.57 (0.52 / 0.05)	0.75
3 19:20	8.450	10.020	2	0.087 (0.073 / 0.014)	0.96
4 19:40	8.380	9.230	1	0.0019	0.999

NAST-I spectral radiances and brightness temperature (BT) were successfully simulated. Since the differences in brightness temperature (BT) between NAST-I and simulations are less then 4%, for all four overpasses, fluxes and heating rates have been computed at all levels at resolution of 0.05 cm-1 for each NAST-I overpass in the Potenza region. The results for the total cooling rates are shown in Fig. 5.

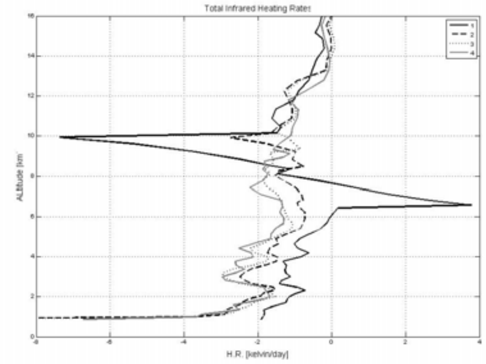

Fig. 5: Total cooling rates in correspondence of the 4 Proteus overpasses the DIFA lidar base.

The cloud effect is evident both in and out the cloud layers. A sensible gradient between cloud top and bottom is developed only in the first overpass. Nevertheless, the total cooling rates show how the radiative forcing seems to be insufficient to explain the complete cloud dissipation. Results for the spectral cooling rates will be show and discussed at the conference, together with results from a clear sky series of overpass on 8 September 2004.

3. SUMMARY

Lidar-derived parameters are fundamental in distributing the IWC inside the cloud depth and thus in determining the cooling rates and layers' energy balance. However, the radiative energy exchange does not explain the whole ice cloud sublimation and microphysics and dynamics need to be accounted for an exhaustive study of a cloud evolution.

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